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PROBLEM OF THE OPERATIONAL RELIABILITY OF FLIGHT CONTROL SYSTEMS AND AUTOMATIC PILOTING OF AIRCRAFT

by Olaf Peters

Dissertation, Technische Universität
Berlin, 1967

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PROBLEM OF THE OPERATIONAL RELIABILITY OF FLIGHT CONTROL SYSTEMS AND AUTOMATIC PILOTING OF AIRCRAFT

By Olaf Peters

Translation of "Zum problem der technischen zuverlässigkeit von flugregelungs-systemen sowie der automatisierung der flügfuhrung von luftfahrzeugen"
Dissertation, Technische Universität, Berlin, 1967

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ABSTRACT

The operational reliability of the currently used manual and automatic aircraft control systems and their components are discussed in the light of the instrumental malfunction and repair estimated statistically by commercial airlines. It is found that the automatic control system malfunction probability derived from the statistics does not meet reasonable reliability standards. Cost estimates are given for the redundant components required to provide adequate air traffic safety standards.

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PROBLEM OF THE OPERATIONAL RELIABILITY OF FLIGHT CONTROL SYSTEMS AND AUTOMATIC PILOTING OF AIRCRAFT

Olaf Peters

1. INTRODUCTION

1.1. Reliability and Flight Safety of Flight Piloting

Operational reliability and the capacity to fulfill a great /1* number of functions are, to begin with, diametrically opposed properties of technical equipment. The more perfect a device becomes with respect to its function, all the more complicated, comprehensive and unreliable it becomes, since its reliability decreases with growing numbers of constructional units. These interrelations were first systematically investigated by Lusser and Pieruschka around 1940 [1], although attempts to attain a sufficiently high operational safety have always been, beside the required function, the goal of all engineering, especially in the field of aeronautics.

The operational reliability of a device is defined as the probability of fulfilling during a certain temporal interval (especially of the flight time of an aircraft) the functions necessary for the carrying out of a task.

That the multiplicity of functions does not represent an insurmountable barrier in regard to reliability is proven by the nature of examples of complicated living organisms. These organisms are so composed that a limited number of malfunctions can be survived. Such faculties should also be realized in greater circumferance with technical equipment, especially in the case of flight piloting systems. The reliability of such systems could be augmented considerably in this way.

The total process of flight piloting is carried out even today by the aircraft pilots, in spite of the fact that many component tasks have been automated. It is a matter here of the control functions, flight control, steering, and navigation, as is presented in Figure 1 after Rossger [2, 3].

To the task of flight piloting belong especially: /2

1. The stabilization of flight attitude and flight velocity (flight control).

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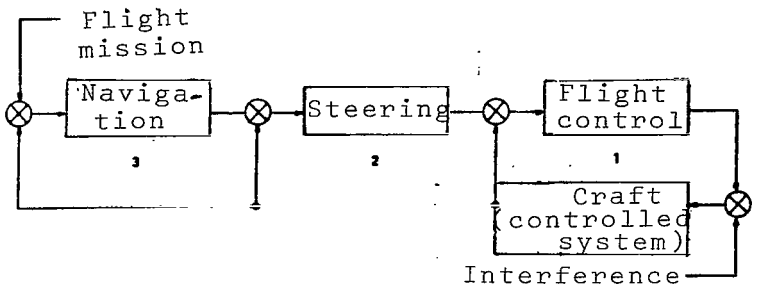


Fig. 1. Control Functions of Flight Piloting.

2. The steering, i.e. control of the bases (altitude, course), through regulation of the path of the center of gravity by altering flight attitude and engine output.

3. The plotting of a prescribed flight program as a task of navigation (optimization of the path line).

The reliability of the flight process should be designated as flight safety, which can be defined in the following way:

Flight safety is the probability that during a given operational time, especially that of an aircraft, no accident will take place concerning the superordinate system, especially the aircraft, with harmful consequences for persons. (Instead of flight time, flight course is also frequently the references magnitude).

The accident probability is the complementary probability for /3
flight safety.

The accident probability results from accident rates.

Figure 2 represents the course of the accident rate of world air traffic as well as total transport in the time span between 1945-1965 according to statistics of the ICAO [4]. The accident rate shows a descending course up to 1955, in order then to recede only slightly more; the total transport, on the other hand, shows an exponentially ascending tendency which corresponds to an annual growth rate of ca. 12%. The absolute number of accident data per year results as the product of accident rate (referred to total transport) and total transport. This number shows to this point only a slightly ascending tendency and, after [4], amounted to in the mean 750 accident deaths per year in the last 5 years.

This situation will, however, alter itself if the accident /4
rate, as in the last few years, remains approximately constant; the total world transport, however, will continue to ascend. The number of annual accident deaths will increase.

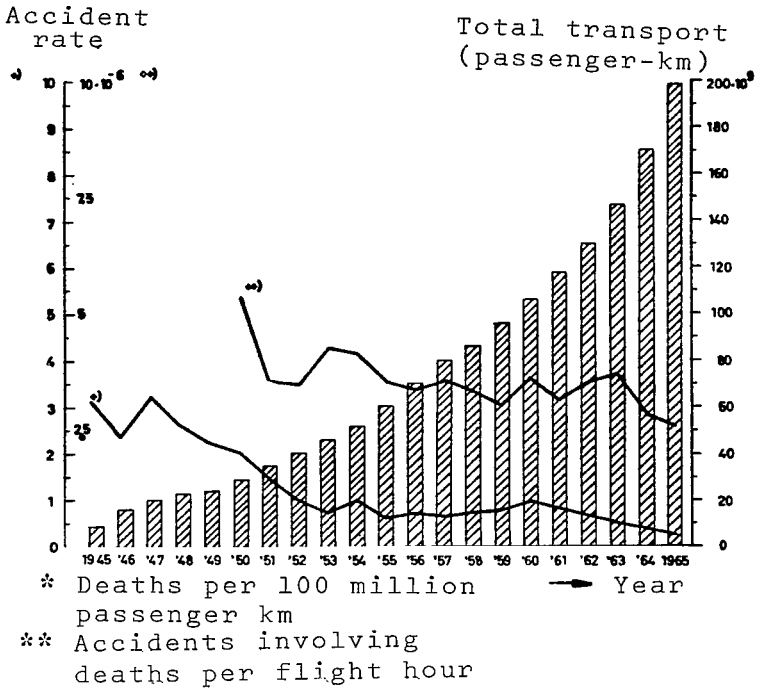

Accident rate
Total transport (passenger-km)
1945 '46 '47 '48 '49 '50 '51 '52 '53 '54 '55 '56 '57 '58 '59 '60 '61 '62 '63 '64 1965
* Deaths per 100 million passenger km
** Accidents involving deaths per flight hour
Year

Fig. 2. Accident Rate Compared With the Growth of Total Transport from 1945-1965.

Figure 3 shows an extrapolation of the present circumstances for the coming decade (after Lundberg [5]), which predicts for the year 1970 a number of ca. 2,000 accident deaths and for 1980 a number of 8,000.

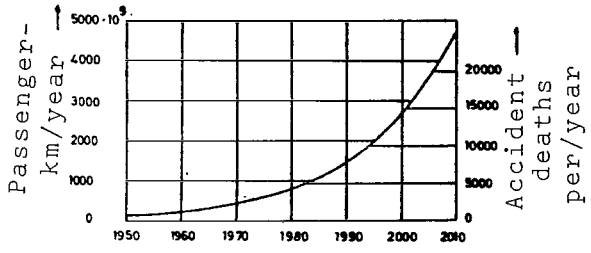


Fig. 3. Advance Estimate of Accident Deaths As Well As Total Transport [5, 7].

Even if these predictions might be afflicted with considerable rate and thus of the accident probability can nevertheless be deduced from them.

If one simply takes the present number of accident deaths of 750/year as given, the accident rate would, with the doubled value of the present traffic load of $200 \cdot 10^9$ passenger-km, which might be reached in 1970, likewise have to be reduced by the factor two.

However, if one considers the planned adoption of large capacity aircraft with transport facilities for 500 persons, the present number ca. 25 accidents of commercial aircraft as a mean value of the last 5 years (after ICAO [4]) would result in a number of 5750 accident deaths at a load factor of 50%, so that a lowering /5

of the accident rate by at least one order of magnitude appears desirable.

In numerical values this demand means:

The accident rate should be lowered from ca. $3 \cdot 10^{-6}$ h^{-1} resp. $5 \cdot 10^{-9}$ km^{-1} to a value of $3 \cdot 10^{-7}$ h^{-1}. (A similar standard for automatic landing has been established after [19] by the Air Registration Board (ARB) of England: the accident probability per landing should not exceed $0.65 \cdot 10^{-6}$).

Figure 4 shows the distribution of accidents over the various flight phases after Hertel [6] and Eggers [7]. It can be seen that more than 50% of all accidents take place during landing, and that nearly 20% of the accidents cannot be traced back to human failure, i.e. errors in flight piloting. It appears questionable whether a decisive improvement of human flight piloting is possible in the case of the already high level training of today.

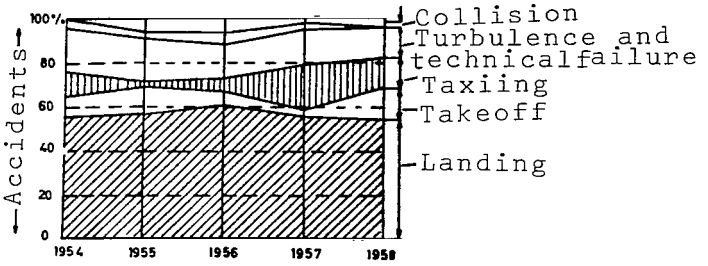


Fig. 4. Distribution of Accidents Over Various Flight Phases According to [6, 7].

The probability of ending a flight without an accident, i.e. flight safety, is essentially the product of the following probabilities: /6

1. Reliability of aircraft frame
2. " propulsion unit
3. " guidance
4. " landing gear
5. " instrumentation
6. " flight piloting
7. " Air Traffic Control and related ground installations

Correspondingly, the total accident probability is the sum of the accident probability of the cited points. As already mentioned, a share of ca. 80% of it falls to flight piloting, so that it appears permissible to equate in the first approximation reliability of flight piloting systems and flight safety.

Accidents which can be traced back to a failure of presently used flight control systems seldom appear in the official statistics of commercial aviation [8]: from 1951 to 1964 only 4 cases are noted, of which 2 were only near-accidents.

The reason for this apparently slight accident rate is less a matter of sufficient reliability of flight control systems, as will be shown, than of the fact that, on the one hand, the especially critical phases such as take-off and landing are not yet automated; on the other hand, the engaged autopilot is continually supervised by the pilot and can be overridden. A few more recent autopilot systems disengage themselves automatically if a malfunction occurs in the system, in order to hold the aircraft in a trim state.

Autopilots have special significance for vertical take-off and landing aircraft (VTOL), since these cannot be stabilized with sufficient flight safety as a consequence to the human lack of inherent stability.

The planned adoption of aircraft for supersonic air traffic /7 makes, moreover, an automatization of the steering and navigation processes necessary as a consequence of small range tolerance as well as for economic reasons.

The adoption of vertical flight techniques has, for example, been recommended for the improvement of flight safety [7]. A further possibility is an improvement of air traffic control, especially of the landing process. The decisive step could take place by means of automating the entire flight piloting process, if success could be attained in making it more reliable than human flight piloting. If flight piloting is transferred to an automatic flight piloting system, its reliability becomes equal to flight safety, i.e. its malfunction probability becomes equal to accident probability.

Thus, the same standard would have to hold true for the reliability, resp. malfunction probability of such a flight piloting system, which has been established for flight safety, resp. accident probability.

1.2. Developmental Phases of Automatic Piloting

1.2.1. GENERAL INFORMATION ON FLIGHT PILOTING

At present, primary partial paths of flight piloting, especially flight attitude stabilization, as well as a part of steering, are automated by means of the flight control systems available today, which are installed on board all larger aircraft. The principal purpose of application of autopilots lies at present in a brief release of the pilot from the task of stabilization and course-altitude bearings. The technical realization of the flight piloting functions, which have been reserved until now exclusively for the

pilot, such as take-off and landing as well as certain navigational/8
tasks, is possible and is being tested.

The essential problems of automatic piloting, flight safety or operational reliability have, however, not been solved to a sufficient extent.

Flight Attitude Stabilization (Flight Control)

Systems which fulfill the task of flight attitude stabilization of aircraft are known as stabilizing autopilots. Gyroscopes which give off torsional signals around an axis for flight attitude or angular velocity serve as sensors. Linear and angular accelerometers are used in addition for the purpose of improvement of control behavior. The signals are prepared in a computeramplifier so that they can control servometers which, for their part, undertake control surface adjustments and thereby influence flight attitude. In high performance aircraft, additional damping gyro regulators often serve the purpose of suppressing vibrations around the various axes. Special significance accures to autopilots in fan VTOL aircraft, since as a consequence of lacking aerodynamic inherent stability, a stabilization by the pilot is normally not possible in hover flight.

Steering (Steering Control)

The steering of the aircraft can be undertaken through the command variable of the stabilizing system in the form of a series control. The influence of the flight attitude, and of the flight path as well takes place either through precession moments in the gyroscope or through direct mixture of the signals in the computers, resp. amplifiers. If the flight piloting through the autopilot takes place manually, these steering signals are removed from the control knobs on the control unit by appropriate mechanical-electrical pickup. With "automatic steering", the steering signals come directly from the same or similar position sensors (navigation re- /9
ceivers, compass-directed course gyro systems or air data transmitters), as they are presented to the pilot in the case of manual flight piloting through indicators. In each case according to mode of operation, the azimuthal (course) piloting is concerned with signals of compassdirected course gyroscopes, the most various radio location systems resp. escecially radio compass (ADF) and VOR resp. landing course receivers of the ILS. But also possible are steering signals with hyperbolic methods, as for example, Decca, as well as signals from Doppler radar systems and the inertial navigation systems especially important for the future. For vertical piloting, signals from barometric altimeters and radio altimeters as well as signals of the glide path receiver ILS come into question. In general, there also belongs to steering the control of flight velocity either by an autothrottle or over pitch angle guidance. The sensors for this purpose are indicators of static air speed and angle of incidence.

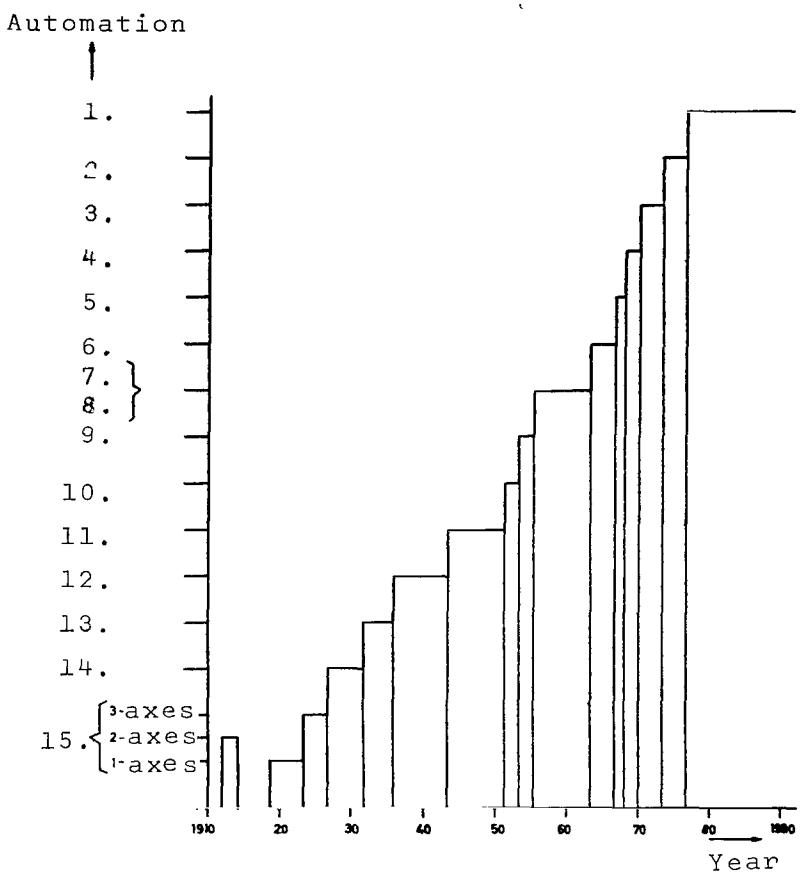


Fig. 5. Automation of Partial Task of Flight Piloting

KEY:

1. Fully automatic flight piloting system;
2. Automatic navigation, (inertial navigation. DME radar. PHI, Doppler);
3. Taxing (landing);
4. Automatic (lift-off and take-off);
5. Leveling off (landing);
6. Auto-throttle;
7. Glide path (ILS);
8. Landing course (ILS);
9. Speed (IAS, Mach);
10. UHF piloting (VOR);
11. Radio-piloting (ADF, NDB);
12. Telecompass piloting;
13. Altitude maintenance (barometer);
14. Steering, manual;
15. Flight attitude Stabilization 3-axes 2-axes 1-axes

Primary elements, amplifiers, actuators are components of the control. Aircraft frame or body and control surfaces form the Controlled System. The description of the controlled system takes place by means of flight mechanics. The optimization of the cooperation of the control system members is the task of control technology.

The totality of all control devices participant in flight piloting should be characterized as the flight control system. A flight control system comprehends, in each case according to complexity, several autopilots for individual functions, as for example:

damping gyro regulator
stabilization control
steering control with several operational types
speed governer (thrust control)
hover control (for VTOL).

The present and possible future transcription of some of the tasks of flight piloting to flight control systems can be seen, presented chronologically, in Figure 5.

1.2.2. STABILIZING DEVICES, AUTOMATIC FLIGHT CONTROL, FLIGHT CONTROL SYSTEMS /11

Four periods can be recognized in the development and expansion of the functions of flight control systems as well as of the influence of the associated operational reliability of the systems; they will be designated subsequently as the first to the fourth generations.

First Generation

The autopilots of the first generation were systems for the stabilization of flight attitude. An azimuthal steering of the aircraft by the autopilot took place toward the end of the first period by means of modulation of compass signals. The first generation comprehended the time span from 1914-1940. The most important systems of this generation as well as their manufacturers in the year of their commissioning are summarized in Table 1 and described in more detail in [10-16].

The first development of autopilots was begun in 1909 by Sperry in New York. In 1914, Sperry won the first prize of 50,000 francs in competition in France with a two-axes autopilot on board a Curtiss Seaplane, "a device which makes flying safer" [10].

After the first World War in Germany, the first automatic flight controls were developed by Capt. Boykow. As a private citizen he set himself the task of automatic stabilization of all three axes as well as turn and bank controls. Boykow called his device "autopilot" and thus around 1930 introduced this designation which has

since become popular [11]. His developments were then taken over by the firm Siemens Apparate & Maschinen (SAM). In spite of Boykow's success with the three-axes control, work was begun on the construction of the course controller Krü [13] in the Siemens-Liemens-Luftfahrtgerätewerk (LGW) in Hakenfelde for reasons of cost and weight of the limitation decided on by Capt. W. Möller at the Askonia-Werken in cooperation with Lufthansa to the control of course axes. The firm Askonia on the other hand, prepared the three-axes flight control A-2 of Sperry in 1934 in Berlin.

TABLE 1. AUTOPILOTS OF THE FIRST GENERATION /12

Manufacturer	Designation by Type	Year
Sperry	Stabilization device	1914
"	A - 2	1932
Siemens	K 4 U	1937
"	K 12	1940
Askania	Lstz 14 c	1938

Second Generation

The autopilots of the second generations are distinguished by increasing application of electronics. The computeramplifiers are tube-complimented. The function of the autopilot is essentially expanded. It not only comprehends the stabilization of flight attitude, but also permits the modulation and maintenance of barometric variables such as altitude and velocity, as well as the modulation of radio navigational aids and landing aids (ILS), preselected curves and manual control through the control unit. This second phase of the development of flight control systems began with the end of the second World War and reached to approximately 1955.

The most widespread systems of the second generation are entered in Table 2.

TABLE 2. AUTOPILOTS OF THE SECOND GENERATION

Manufacturer	Designation by type	Year
Sperry	A - 12	1945
Smiths	SEP - 2	1946
Eclipse-Pioneer (Bendix)	PB - 10	1946

Third Generation

The flight control systems of the third generation (ca. 1955- /13 64) employed computers and amplifiers to a larger extent. The functions of the devices have been expanced at this time up to the point of automatic landing (SEP-4 in the military domain). An autothrottle is not always an integrated component of these systems.

TABLE 3. FLIGHT CONTROL SYSTEMS OF THE THIRD GENERATIONS

Manufacturer	Designation by type	Year	Aircraft Model
Smiths	SEP-4	1956	Comet, Viscount
Sperry	SP-30	1956	DC-8
Eclipse-Pioneer (Bendix)	PB-20	1957	B-707/720
Lear	L-102	1958	Caravelle (SE 210)
Sperry	SP-50	1962	B-727

Fourth Generation

A striking characteristic of the flight control systems of this most recent generation is the partial application of redundancy. The "multiplex" philosophy, i.e. the use of several control channels functioning in a parallel fashion, was developed by the English firm Smith and was first employed in the autopilot system SEP-5, which is installed at this time as the duplex version in the H.S. Trident, and as the triplex version in the military aircraft Short Belfast. The expansion of the function of the autopilot system and automatic landing required, technologically a certain expenditure and greater standards of the reliability of the systems [17-21]. The development of vertical take-off techniques (VTOL) brought stricter demands to the reliability of flight control systems. The reliability of flight control systems is of such great significance, in this case for flight safety, since, as mentioned, a stabilization of flight attitude by the pilot during the process of physical take-off or landing is not possible in consequence of lack of natural aerodynamic stability.

Table 4 names a few flight control systems of the fourth gen- /14 eration.

Flight Control System SEP-5 (Smiths)

The flight control system SEP-5 is produced at present in two variations (compare 4.2).

TABLE 4. A FEW FLIGHT CONTROL SYSTEMS OF THE FOURTH GENERATION

	Manufacturer	Designation by type	Year of commissioning	Aircraft type
Conventional aircraft	Smiths	SEP-5	1964	Trident, Belfast
	Elliot	AFCS f. VC-10	1964	VC-10
	Smiths	SEP-6	—	—
	Sperry	SP-77	1967	B-737
VTOL	Honeywell	MH-123	1961	VJ-101-C
	Smiths	+)	1964	Do-31
	Elliot	++)	1964	div. VTOL

+)++) Proposals for VTOL autopilots.

1. As "Duplex"-version for the aircraft H.S. Trident of BEA
2. As "Triplex"-version for military transport aircraft "Belfast" (Short Bros, and Harland).

Automatic Flight Control System (AFCS) of Elliot for the VC-10

Elliot Bros., Ltd., England [22] had developed a flight control system for the VC-10 on the basis of the flight control system PB-20, (Bendix). /15

Special techniques of redundancy come into use here, which e.g., also provide a subdivision of the control surfaces. Ailerons are twice subdivided per surface, the side rudder three-fold. The control of the surfaces can be seen in Figure 6 in the example of the side rudder. The three side rudder damping gyro regulators (of those, one standby system) function in parallel fashion with the pedals of the pilot [23].

The actual flight control system is "duplicated-monitored" according to the specifications of the manufacturer and is presented in Figure 7.

The designation "duplicated-monitored" characterizes a quadruplex redundant system which is broken down into two double main systems. One main system contains each assembly in so-called "monitored" fashion [22, 23], in principle dually redundant. It is possible by means of this to permit indications of errors (i.e. differences between assembly and its monitoring units), or to use them for the activation of an auto-changeover unit to the second named system. (At present, the auto-change-over is carried out by the pilot). In this way a malfunction in the system can be survived. /16

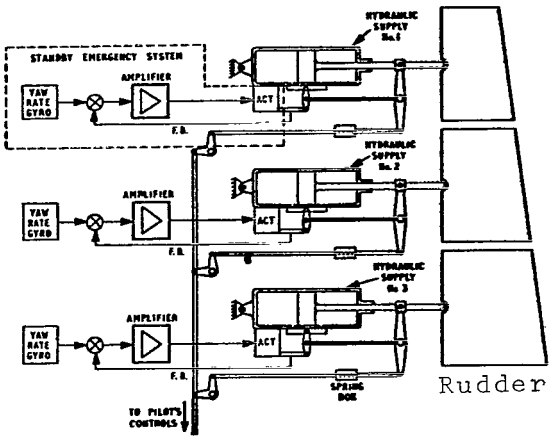


Fig. 6. Side Rudder Control (Schematic) of VC-10 After [23].

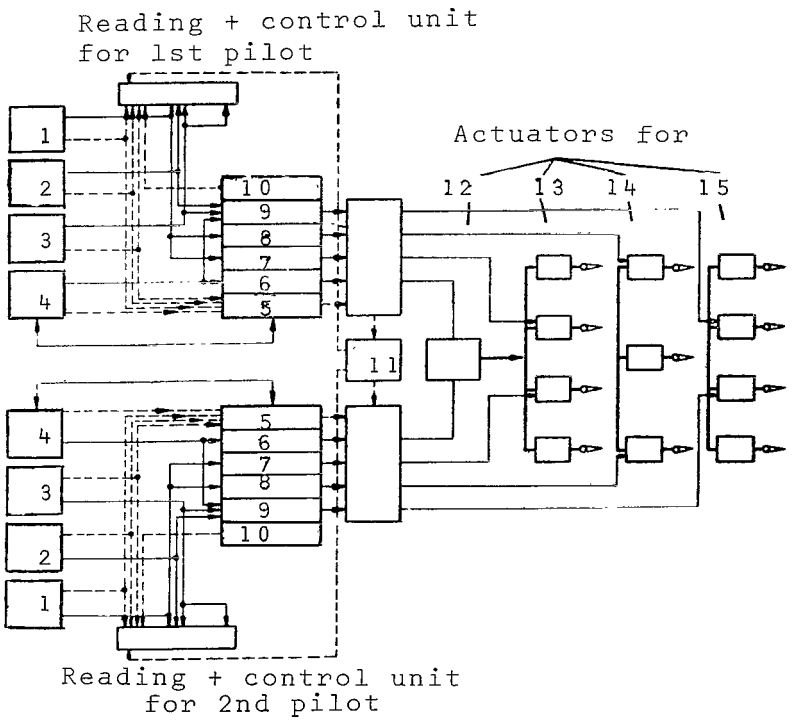
Flight Control System Sperry SP-77

The flight control system SP-77 was designed for the aircraft Boeing B-737 and represents an advanced development of the SP-50 [24]. /17

Developments of the German Autopilot Firms After The Second World War

Fluggerätewek Bodensee

The Fluggerätewerk Bodensee is, as a successor firm of Askania under the direction of W. Möller, concerned with the development of autopilots for VTOL and conventional aircraft. The tendency is to create a universally applicable-so called— standard autopilot. There are at present several types of autopilot which have been tested in various aircraft, such as VJ-101, Nord 2501, Do-31 as well as in a number of civilian air-



1. landing course receiver
2. glide path receiver
3. radio altimeter
4. air data computer
5. monitor
6. throttle
7. roll
8. yaw
9. pitch
10. monitor-autopilot
11. change over
12. engines (thrust)
13. ailerons (divided)
14. side rudders (div.)
15. elevators (divided)

Fig. 7. Flight Control Systems of the VC-10 (Principle Presentation) After [23].

craft. The single axis autopilot FRG-5-3 has been permitted in the civil domain since 1960.

The heightened demands of the VTOL-technique, for which the Bodenseewerk autopilot for the aircraft VJ-101 and Do-31 as well as for the AVL German-American project provides have occasioned the beginning of planning and development of redundant autopilots.

Vereinigte Flugtechnische Werke VFW
(previously Focke-Wulf and Weser Flugzeugbau)

The VFW in Bremen is concerned with the development of an autopilot which is conceptualized for the vertical take-off fighter plane VAK-191.

The first proposal for this autopilot type of the VFW is concerned with a triplex redundant, intermeshed type (designated by VFW as the "Triplex" autopilot) which provides a triplex arrangement of assemblies, gyroscopes and amplifiers. Three position gyros are provided as primary elements, which give off each signal proportionally to deviation from position. In order to obtain a signal proportional to angular velocity, the position signal is elec- /18
trically differentiated in the amplifier [25, 26].

Details on the developmental history of flight control systems are found in:

Wendroth [27], Johnson [28], von Manteuffel [11], Wiren [29], in Draper [30], Richardson [31], Blakelok [32] and [10].

1.2.3. FURTHER PUBLISHED PROPOSALS FOR REDUNDANT FLIGHT CONTROL SYSTEMS

Aside from the attempt to heighten systems reliabilities through improvement of the reliability of assemblies and constructional units, further proposals for redundant executions of autopilots have been made known aside from the already mentioned systems of the firms Smiths, Elliot and Honeywell.

1. Beside the discussion of the advantages of an adaptive flight control system, triplex redundancy is recommended by Whitaker and Kezer (Massachusetts Institute of Technology) [33] with reference to the development of the firms Smiths and Elliot (Fearnside [34] and Howard [19].

2. General Electric investigates in [36] the possibility of an adaptive redundant flight control system.

In a recent publication (1966), the adaptive, triplex redundant flight control system of General Electric is described for the military aircraft F-111 equipped with variable sweep wings [37].

3. Report is made in [38] on the development of a duplex redundant, adaptive autopilot by Sperry.

4. Bendix (Eclipse-Pioneer Div.) makes a proposal in [39]/19 for a triplex damping gyro regulator with automatic error detection, functioning according to the majority principle. The majority principle is discussed in more detail in [40].

5. Reports are made in [49] and by Howard [42, 43] on proposals of the firm Elliot, especially for VTOL-hover autopilots. Reference is made there to the advantages of the chosen design principle of "integral redundancy".

6. The flight control system of Lear-Siggler, Inc. for the aircraft Ling-Temco-Vought A-7a (Corsaire 2) of the American Navy, on which a report is made in [44], is also duplex redundant.

7. New proposals from various manufacturers for redundant VTOL-hover autopilots (Fluggerätewerk Bodensee, VFW, Elliot Bros., Hawker Siddeley Dynamics, Smiths Av.-Div.) for the aircraft Dornier Do-31 and VFW VAK-191 have been published and investigated in their own theoretical analysis and compared [25].

8. Further, in [48-55] reports are presented on proposals for redundant autopilots.

9. Pfaff [46] gives a survey on a few possibilities of improving the reliability of autopilots through redundant executions.

An attempt to classify the various redundant arrangements of assemblies and control channels in the case of autopilots was made by Rosser and this author in [47].

1.2.4. AUTOMATIC LANDING

The difficulties invested in making automatic landing possible/20 have two reasons.

1. Flight safety: the accident-cause statistics (Fig. 4) show that landing is that particular flight phase in which most fatal accidents occur.

2. Economic considerations: according to Rosler [56] such poor weather exists at the airports of the world an average of 200 hours per year (based on statistics of the American Air Weather Service) that the present approach minima for jet aircraft are not met. For propeller driven aircraft, the number lies at 120 hrs/year. The loss which results from this for civil aeronautics is estimated at 400 million DM/year. For these two reasons, the efforts are

great which are made on an economic level, and by the government (ICAO) as well as by the commercial airlines (IATA), in order to attain all-weather landing. In Germany the basic principles are being established by the "Arbeitskeeis Blindlandung".

The efforts in the direction of being able to carry out landings under any weather conditions go back to the years of the adaptation of flying by instrument. In 1932, Gloeckner [57] gives in the 284-th report of the DVL, Berlin-Adlershof a summary on procedures and possibilities for blind landings in which the guide cable method (Cooch, Hanson, Loth) as well as the glide path method (Diamond, Dunmore) are described, which were later taken up again by the B.L.E.U.

Special efforts in the area of the development of an operational automatic landing system had been made in England. The Blind Landing Experimental Unit (B.L.E.U.) of the Royal Aircraft Establishment Bedfort has carried out fundamental studies in cooperation with the firms Smith Standard Telephones & Cables (radio-altimeters) and Murphy-Radio (pilot cables) [58, 59]. The principle item of an automatic landing system is comprised of a flight control system expanded in function (SEP-2). The altitude above ground (vertical piloting) is controlled in the final approach and leveling off phase by a radio altimeter. /21

A special problem is presented by azimuthal piloting, since the available landing course transmitters of the ILS-system did not permit a sufficiently precise piloting to appear possible. For that reason, the azimuthal piloting through a pilot cable system laying parallel to the landing path was employed [60].

The B.L.E.U.-system is continually being developed, especially by the Smith Av. Division [61, 62] and is today in the developmental stages of "auto-flare" and "auto-land", the first-developed auto landing system [63]. The main component consists of the flight control system SEP-5. In the aircraft H.S. Trident of the British European Airways, the "auto-flare" system with azimuthal piloting by the pilot during the leveling off and landing has been installed in series with the SEP-5 autopilot in duplex versions. The "auto-land" also has a complete automatic azimuthal piloting that is presently in testing.

The flight control system SEP-5 is installed in this case as a triplex-system (since the November 18, 1964 in the experimental aircraft Trident G-ARPB). In the time from June to December, 1966, 400 auto-flare landings were carried out in the normal line of traffic of the BEA [64]. /22

The problem of the azimuthal exact piloting in the case of "auto-land" procedure has come closer to a solution by the development of a new, more precise ILS-system [65]. The pilot cable method long ago proved to be too expensive for reasons of installation and cost.

AUTOMATIC LANDING SYSTEM

No.	Designation	Producer	Flight Control System	Azimuthal Piloting	Vertical Piloting	Aircraft Type
1	BLEU-System	Smiths Av. Div. Standard Tel. A. Cables, Murphy Radio Ltd.	SEP-2 (Smiths)	ILS-LOC Leitkabel	ILS-GP Radio Altimeter	Tested in Varsity, Canberra, DC-7
2	Auto-Land-System	Smiths Av. Div.	SEP-5	ILS-LOC	ILS-GP Radio Altimeter	H.S. Trident, Short Belfast
3	Automatic Landing System	Elliot Bros.	VC-10 AFCS Elliot 2100	ILS-LOC	ILS-GP Radio Altimeter	VC-10 BAC-111
4	AWLS	Lear Siegler	L-102 L-102	ILS-LOC	ILS-GP Radio Altimeter	SE 210 Caravelle
5	ALS (AN-GSN-5)	Bell		Tracking radar and data link	Tracking radar and data link	No Spec. Type
6	APN 114	Autonetics Div. of North-American		ILS-LOC	ILS-GP Radio Altimeter Aclrmtr.	No Spec. Type
7	RAILS	Bell				Helicopter

Also under consideration is installing in the place of the conventional optical landing path lighting, microwave radio ranges whose position can be reflected to the pilot through antennas and computer-receivers onto the windshield as a head-up display, which, however, can also take over the automatic course bearing through servomotors.

In civil air traffic, Elliot Bros. have also carried out developmental studies on the VC-10 and BAC-11 [66, 17] as well as Lear-Siegler on the SE-210 (Caravelle) [67]. Considerations on the reliability of the landing system are found in [21, 19, 68]. In the military domain there exists a number of automatic landing systems, especially on aircraft carriers.

In [69] a survey of the present state of automatic landing is presented.

The mentioned automatic landing systems and further proposals are presented in Table 5. However, only Nos. 1-4 are of significance for civil aeronautics.

Automatic landing is to be introduced into commercial aviation/24 in three operational categories in accordance with recommendations of the ICAO [70]: the categories are schematically represented in Figure 8.

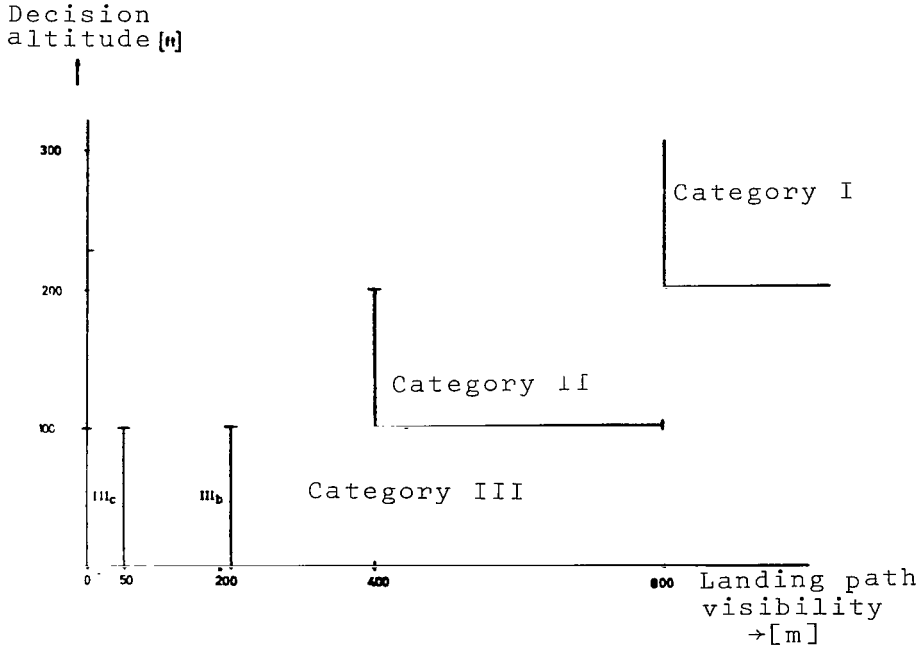


Fig. 8. Categories in Landing

1.2.5. AUTOMATIC TAKE-OFF

During the take-off phase, orientation by the pilot generally takes place visually, i.e. through optical orientation of the runway and its lighting. An automation of this process is being considered at this time. It would therefore be conceivable, as in the/25 case of automatic landing, e.g., with the help of improved landing course transmitters of the ILS system, to realize an automatic azimuthal piloting on the runway as well. A later problem is presented by the monitoring of the velocity conduct of the aircraft.

In order to release the pilots from a few of the tasks accumulating during take-off, proposals have been made known recently for adapting as an initial stage of an automation of the take-off process so called "take-off monitoring" which are developed as flight directors. Such proposals have been made by the firms Smiths, Sperry, Honeywell, Elliot, etc., as well as by Fricke [71]. However, as in the case of "auto-flare", in all of these systems only the monitoring of path velocity and of the movements around the pitch axis takes place. The azimuthal piloting around the vertical axis must be carried out by the pilot himself.

The complete automation of the take-off procedure would require in addition:

1. The solution of azimuthal piloting on the runway, as in the case of fully automatic landing.
2. The carrying out of the command signals of the take-off monitoring system by means of actuators, which represents, in principle, no difficulties.

2. MALFUNCTION RATES

2.1. General Information

2.1.1. MALFUNCTION CAUSES - PHYSICS OF DEFECTS

2.1.1.1. Connection Between Stress and Malfunction

Although consideration of reliability is based on the statistical-probability-theoretical observation of malfunctions and defects, a more comprehensive consideration must nevertheless also concern itself with the causes of a malfunction and the malfunction mechanism itself. This is especially necessary if an improvement of reliability is to be brought about by an improvement of the constructional units. The malfunction mechanism differs for each type/26 of action and constructional unit. However, certain divisions can be made according to the type of acting stress and according to the malfunction mechanism. A common malfunction which, of course, represents an impermissible deviation of an actual value from the theoretical value, is caused by the absorption of an energy form differing in each case, if this factor, generally called stress, exceeds a threshold value. This threshold value is given by the inherent capacitance of the component in question. An exception is formed by the contamination in which adhesions and adsorption effects play a role as energy forms. Only in a very few cases can a formal, strict context be precisely indicated between stress as the cause and its effect, the malfunction.

2.1.1.2. Stresses

A subdivision can be undertaken:

1. Operational Stresses
2. Stresses Caused by Environment

By operational stresses are meant stresses which affects constructional units or assemblies through functional operation. Through effective design, these can assume values, especially in the electrical equipment, which exceed the capacitance of the components and thus lead to malfunction. Capacitance measurements serve the purpose of identifying such local stresses.

Stresses caused by environment originate through external influences and are imitated in longevity tests through simulation of environmental conditions.

On the other hand, a division according to type of the acting energy form is possible.

1. Thermal Action /27

2. Mechanical Action
   2.1. Action of Forces, Torsional Moments and Pressures
   2.2. Action of Inertial Forces, resp. Acceleration

3. Chemical Action and Contamination

4. Action of Field Magnitudes and Electrical Currents
   4.1. Electrical Fields
   4.2. Magnetic Fields
   4.3. Gravitational Fields

5. Ionizing Radiation
   5.1. Electromagnetic Radiation
   5.2. Corpuscular Radiation

Furthermore, the duration of stress is important.

Here, a distinction must be made between the static case of a regular load, where E = const. and an alternating stress E = f(t) are distinguished. It has been shown that alternating stresses have a much greater influence on fatigue and aging than static stresses.

Stresses have, in general, a stress spectrum, whose course is given by the task-related environmental conditions. The occurring stresses will differ extraordinarily as well, in each case according to installation, location and utilization of the equipment in question.

/28

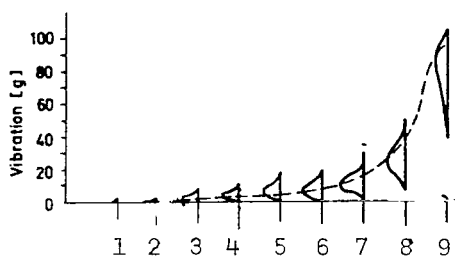


Fig. 9.

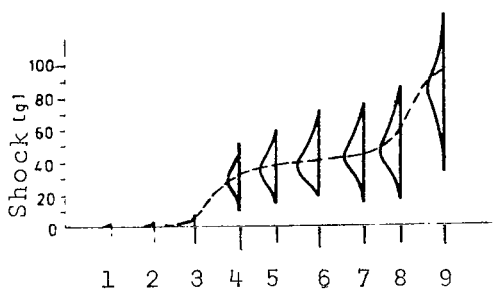


Fig. 10.

Vibration and Shock Distributions in the Case of Various Installations and Environments after [89, 90].

1. Satellite
2. Laboratory
3. Ground
4. Ship
5. Ground Vehicle
6. Railroad
7. Aircraft
8. Early Rocket
9. Present Day Rockets

Figures 9 and 10 show the distributions of vibration and shock, as they were ascertained for various installations; Figures 11 and 12 the distribution of temperature and moisture after [89, 90].

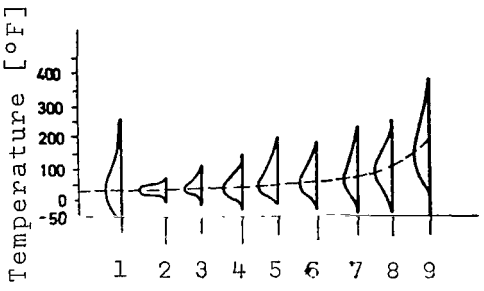


Fig. 11.

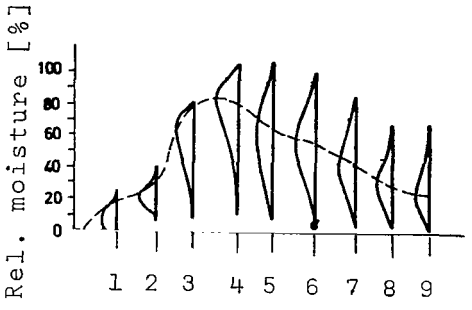


Fig. 12.

/29

Temperature and Moisture Distribution in Various Installations and Environments [89, 90].

1. Satellite
2. Laboratory
3. Ground
4. Ship
5. Ground Vehicle
6. Railroad
7. Aircraft
8. Early Rocket
9. Present Day Rockets

2.1.1.3. Malfunction Mechanisms

If a malfunction occurs as a result of a stress which exceeds the threshold value of the highest permissibe stress, or of a contamination, this malfunction will happen in a certain way. A few malfunction mechanisms are noted in Table 6. /30

It must be considered that the energy forms can be converted into one another. Thermal stresses also cause mechanical stresses, and conversely.

2.1.1.4. Material Engineering

The field of material engineering [73], the materials available for a technical realization must be described in their characteristic magnitudes in such a way that a rational dimensioning can take place under consideration of the appearing stresses; on the other hand, improvements of certain properties of the material (e.g., by means of heat treatment) should be able to be undertaken through more precise knowledge of the properties of solids. To that belong properties such as hardness, ductility, creep strength depending on time, resistance to corrosion, and in plastics especially heat resistance and resistance to radiation. Also, the problems of an /31

TABLE 6. MALFUNCTION MECHANISMS

Type of Action	Thermal	Chemical & Contamination	Mechanical	Field Magnitudes Currents and Radiation
Type of Malfunction	Alterations of Length	Corrosion	Deformation	Sparks
	Alteration of Conductivity	Aging	Break	Electric Arcs
	Boiling Over	Diffusion	Damage of Surfaces	Inductive Disturbances
	Evaporation	Charge	Flowing	Scatter Effects
	Freezing	Discharge	Tolerance	Coupling Effects
	Fatigue	Evaporation	Aging	Overloading
	Recrystallization	Sublimation	Destruction	Distruction of Insulation
		Destruction of Coatings and Surfaces	Erosion	Instability
		Adhesion	Fatigue	Static
			Leakage	Short Circuit
			Unbalance	Radiation Damage
			Wear	Interruption Drifts
			Friction	Charge Discharge

optimal designing with respect to stress capacity are included in the problem of a reliable construction. The description of investigations on determining material properties is carried out with the help of statistical methods.

2.1.2. STATISTICS OF MALFUNCTIONS

2.1.2.1. Presentation in the Form of Malfunction Rates[1]

Since the reliability theory is based on the statistical evaluation of defect frequencies and their temporal dependence, it is purposeful to define a magnitude suited for the description of the events, this is, e.g., the malfunction rate h(t).

$$h(t) = \frac{1}{N(t)} \cdot \frac{dN}{dt} \tag{1}$$

In the evaluation of statistics as well as in the experimental determination of malfunction rates, the differential magnitudes dN and dt must be replaced by the measurable magnitudes ΔN and t. Then, /32

$$h(t) = \frac{1}{N(t)} \cdot \frac{\Delta N}{\Delta t} \tag{2}$$

where

ΔN = number of malfunctions in the considered temporal interval Δt
N = number of components available at time t.

Frequently, variables defined in another way, as for example the malfunction density f(t), are more suitable for the description of the malfunction behavior. However, the malfunction rate will be employed subsequently.

If defective systems are replaced in the interval Δt by new ones, the following relation is equivalent:

$$h(t) = \frac{\Delta N}{\sum t_i} \tag{3}$$

where $\sum t_i$ is the sum of the operational times of all components since

$$\sum t_i = N \cdot \bar{t}_i$$

The calculation of the reliabilities, resp. the malfunction probabilities of flight control systems is then especially simple if the malfunction rate assumes a temporally constant value, thus

$$h(t) = \lambda = \text{const.} \tag{4}$$

[1] Compare [74-82].

To what extent the assumption of a constant malfunction rate is justified will have to be tested subsequently.

It cannot be seen from the statistics of the commercial airlines whether the malfunctions have appeared as interruptions or as short circuits. It is necessary in principle for consideration of redundency (compare 5.2 ff) to indicate the malfunction rate of a system or an assembly in different terms as malfunction rate λ_o (interruption compound, zero signal) and as malfunction rate λ_o (short circuit, false signal, "Hardover"). /33

However, it can be established as a precondition in the considered autopilots and assemblies of autopilots that the number of malfunctions as interruption resp. zero signal is very large with respect to the number of malfunctions as short circuits, thus

$$\lambda = \lambda_o \qquad (5)$$

2.1.2.2. Remarks on the Statistics of Commercial Airlines

The statistics of commercial airlines distinguish between a premature removal and defects in devices of the aircraft equipment actually verified, since it is shown that the statistics for these events shows very different figures.

The premature removal of equipment takes place for the most part as a result of a complaint of the pilot and confirmation by a competent ground mechanic.

Then, no defect resp. malfunction can be found in the workshop in part of the prematurely removed equipment. Table 7 reconstructs, as an example, the ratio of premature removals to actually verified defects for 20 assemblies of the aircraft Boeing 720 of United Air lines.

The mean value results here in a relation of d = 2.16, i.e. on the average 2.16 times as many removals are undertaken than would have been necessary according to the number of actual malfunctions which have appeared.

Accordingly, it is meaningful to differentiate, in the consideration of such statistics, between the removal rate and the actual malfunction rate.

The removal rate E is the number of prematurely removed units, referred to the total number of flight hours of all equipment

$$E = \frac{\Delta N_1}{\Sigma t_i} \qquad (6)$$

TABLE 7. RATIO OF REMOVALS (APPARENT MALFUNCTIONS) TO ACTUAL MALFUNCTIONS)[2] OF VARIOUS FLIGHT EQUIPMENT /34

Equipment Designation	Number of Removals (Apparent Malfunctions) N_1	Number of Actual Malfunctions N_2	Ratio $d = N_1/N_2$
Amplifier-Computer	113	41	2,75
Accessory Unit-WX Radar	68	15	4,50
Headset-Minitel	118	64	1,85
Control-Auto Cabin Press.	56	41	1,35
Indicator-WX Radar	44	23	1,90
Computer-Copilot	43	16	2,70
Chassis-Kifis-Control	43	29	1,50
Interrogator-DME	85	53	1,60
Recorder-Flight-Data	41	17	2,40
Computer-Pilot	41	15	2,70
Transmitter/Rcvr-WX Radar	41	20	2,05
Coupler-Mach Trim	38	10	3,80
Receiver-VHF Comm/Nav	141	64	2,20
Brake-MLG	271	261	1,05
Dispenser-Coffee Maker	63	45	1,40
Receiver-ADF	62	38	1,65
AMP-Public Adress	30	12	2,50
Gyro-Vertical	60	32	1,85
Transmitter-VHF	58	36	1,60
Indicator-Horizon Flight Dir.	54	29	1,85

The malfunction rate λ is, corresponding to that which was said above, if d and E are known: /35

$$\lambda = \frac{E}{d} \qquad (7)$$

2.2. Malfunction Rates of Flight Control Systems

2.2.1. EVALUATION OF STATISTICS

The statistics obtained by the commercial airlines on premature replacements, as well as on maintenance and repair corvices on air-

[2] UAL (United Air Lines) Reference time: March - May, 1965, Boeing 720, 25495 Flight hours.

craft and equipment, make possible an evaluation with respect to removal and malfunction rates of installed flight control systems and their components. The results of such evaluations are reconstructed in the following sections.

First Generation

No data are available to us on the malfunction rates resulting in flight operation of autopilots of the first generation. However, an attempt will be made under 4.2 to make a statement on the malfunction probabilities of these systems with typical values of the malfunction rates of autopilot assemblies which were obtained in 2.3.

Second Generation

PB-10 (Bendix) and A-12 (Sperry)

The autopilot PB-10 of the Eclipse-Pioneer Div. of the Bendix Corp. was used, for example, in the aircraft of the type Douglass DC-6. The Sperry A-12 was employed in the Convair CV 340 (Metropolitan). The United Air Lines fleet consisted essentially of these two aircraft types in the time span beginning in 1948. The removal rate (Fig. 13) shows an essentially smaller value after the introduction of the autopilots as well as a falling tendency. This was able to be attained by an improvement of maintenance and various improvements on the flight control systems themselves. /36

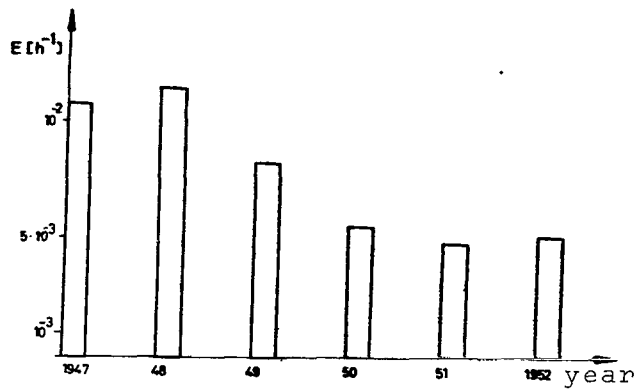


Fig. 13. Revoval Rates of the Autopilots of United Air Lines Fleet [83] in the Years 1947-1952.

The autopilot system PB-10A (Bendix Corp) is likewise installed in the aircraft of the German Lufthansa of the type Lockheed L-1049 G (Super Constellation and Vickers V-814 (Viscount). The PB-10A is a further development of the type PB-10.

Since a greater number of complaints about these autopilots resulted from the part of the flight personnel, the LH performed a

special investigation on the main sources of error on these instruments. In the time span from 7/1/62 - 6/30/61, 294 premature removals resulted in these flight controls after a total of 43,469 flight hours [85] (block to block time); in 194 removals (ca. 56%) no defect was able to be verified. The results of the statistics complaints to the number of actually verified defects amounted here to /37

$$d = 2.26$$

TABLE 8. REMOVALS AND MALFUNCTION RATES OF THE PB-10A IN THE TIME SPAN 7/1/60 - 6/30/61 [84] (GLH)

Premature Removals	294
Actual Defects	130
Number of Flight Hours	43,469
Removal Rate	$6,763 \cdot 10^{-6}$
Malfunction Rate	$2,990 \cdot 10^{-6}$

Table 9 reconstructs the distribution of appeaing errors over the individual assemblies of the system.

TABLE 9. DISTRIBUTION OF MALFUNCTION RATES OVER THE ASSEMBLIES OF THE PB-10A [84] (GLH)

Assembly	Portion (%)	Malfunction Rate
Rate Gyro	27,97	$10,81 \cdot 10^{-4}$
Flux Gate Ampl.	20,82	8,05
Altitude Control	11,90	4,60
Vertical Gyro	5,95	2,30
Integrator	8,33	3,22
Servos	7,14	2,76
Master Direction Ind.	5,36	2,07
Magnetic Ampl.	2,38	0,92
Trim Servo	1,78	0,69
Sonstiges	8,33	3,22
	100,00	

Third Generation

SEP-4 (Smiths Aviation Div.) /38

The malfunction rates after 83,880 flight hours[3] presented in

[3] Accomodatingly put at our disposal by Smiths/VDO.

Table 10 resulted with the auto pilot SEP-4 of the Smiths Aviation Div., as it is installed in the fleet of 59 aircraft of the type Vickers Viscount of the BEA.

TABLE 10. MALFUNCTION RATES OF THE SEP-4 IN THE AIRCRAFT VISCOUNT OF THE BEA IN THE TIME SPAN 1961/62

Assembly	Malfunction Rate
Gyro Unit	$3{,}5 \cdot 10^{-4}$
Amplifier	4,5
Flight Panel	3,3
Coupling Unit	4,2
Elevator Servo	0,5
Torque Limiter	0,3
Safety Switch	0,2
Aileron Servo	0,3
Other	0,6
Total	$17{,}4 \cdot 10^{-4}$

TABLE 11. MALFUNCTION RATES IN THE SEP-4 IN THE AIRCRAFT COMET OF THE BEA IN THE TIME SPAN 1961/1962

Assembly	Malfunction Rate
Amplifier	$4{,}9 \cdot 10^{-4}$
Locking Unit	4,9
Pressure Unit	4,9
Flight Panel	4,6
Gyro Unit	2,2
Elevator-Trim Servo	0,9
Elevator Servo	0,8
Other	1,0
Total	$24{,}2 \cdot 10^{-4}$

The malfunction rate of the autopilot SEP-4 in the aircraft type Comet of the BEA yielded the values presented in Table 11 with, on the whole, 34,141 flight hours in the time span 1961/1962.

The ca. 50% larger malfunction rate of the SEP-4 in the jet aircraft, as opposed to the same autopilot in the turboprop aircraft Viscount, might result from the higher environmetal stress (temperature, vibrations, shock).

SP-30 (Sperry Phoenix Corp.)

The autopilot SP-30, of the Sperry firm, is installed in the aircraft of the Douglas DC-8 type of United Air Lines. The fleet included 38 aircraft of this type in the time span under consideration.

Table 12 shows the number of premature removals and the total number of flight hours after data of United Air Lines[4], as well as the removal and malfunction rates calculated from them.

A mean value of the malfunction rate results:

$$\lambda = 35.3 \cdot 10^{-4}$$

[4] Accommodatingly put at our disposal upon request.

TABLE 12. REMOVAL AND MALFUNCTION RATES OF THE SP-30 /40

Time Span 1965	Jan.	Feb.	Mar.	Apr.	May	June	Mean Value (Jan-June 1965)
Number of Premature Removals	88	80	91	97	95	85	
Total Number of Flight Hours	12,293	11,210	12,614	12,324	13,555	14,182	
Removal Rate	72	71	72	79	70	60	$70.6 \cdot 10^{-4}$
Malfunction Rate	--	--	--	--	--	--	$35.3 \cdot 10^{-4}$

correspondingly, an MTBF of 306 hrs.

It can be likewise be seen from the table that the removal rate and thus the malfunction rate, of the entire flight control system fluctuates only slightly from month to month. A gradient or falling tendency is not recognizable, i.e. the assumption of a temporal constancy of the malfunction rate would be justified in this case.

Flight Control PB-20 D (Bendix)

The number of premature removals and the number of flight hours according to the data of United Air Lines, as well as the removal and malfunction rates calculated from them, are reconstructed in Table 13. The fleet of aircraft equipped with this autopilot included 29 aircraft of the type Boeing B 720 in the time span under consideration.

There results for the autpilot PB-20 a mean value of the malfunction rate of

$$\lambda = 50.1 \cdot 10^{-4} \ h^{-1}$$

at a removal rate of $E = 100.2 \cdot 10^{-4} \ h^{-1}$. That corresponds to an MTBF of 200 hrs.

The fluctuations around the mean value of the removal rate are larger than in the case of SP-30. The assumption of a temporally constant rate might, however, be justified here.

TABLE 13. REMOVAL AND MALFUNCTION RATES OF THE PB-20 /41

Time Span 1964/65	Oct. 1964	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Oct-June (Mean Value)
Premature Removals	81	62	102	104	80	90	78	69	73	
Total Number Flight Hours	8,236	7,883	8,168	8,431	7,595	8,418	8,348	9,129	8,511	
Removal Rate $E \cdot 10^4$	98	79	125	123	105	107	94	85	86	120.2
Malfunction Rate $\lambda \cdot 10^4$	-	-	-	-	-	-	-	-	-	50.1

Statistics of Air France[5]

Air France likewise has the autopilot type PB-20 in operation in its fleet of 24 aircraft of the Boeing 707 type. In Table 14, the number of actually verified malfunctions and the number of corresponding flight hours for the main assemblies is compiled for the year 1964. The malfunction rates and the MTBF were calculated from them.

TALBE 14. MALFUNCTION RATE OF PB-20 /42

Assembly	Number of Malfunctions	Number of Flight Hours	MTBF [h]	Malfunction Rate $[h^{-1}]$
Amplifier Computer	84	56 925	680	$14,80 \cdot 10^{-4}$
Air Data Sensor	43	65 250	1 510	6,63
Vertical Gyro	62	103 025	1 660	6,03
Stabilizer Trim Servo	71	60 225	850	11,50
Surface Servo Actuator	29	152 800	5 200	1,92
Total	289	—	—	$44,96 \cdot 10^{-4}$

5 Accommodatingly placed at our disposal upon request.

There results a malfunction rate of the autopilot of

$$\lambda = 44.96 \cdot 10^{-4} \quad h^{-1}$$

and an MTBF of 223 hrs.

Take-off-reliability of aircraft B-707/720 with the flight control system PB-20.

A gauge for the reliability of the operational equipment, especially that of the flight control system, is the probability that a planned flight will be carried out at a certain take-off time. A flight is not delayed, which begins ± 15 minutes within the planned take-off time. The take-off-reliability is frequently designated as availability in the reliability theory.

The evaluation of the statistics of three civil airlines with aircraft types Boeing 707-720 in the period of time from January to November 1962 with, all told, 82,187 takeoffs, is shown by Table 15 after [86]. /43

All told, there results a relative takeoff-delay frequency, resp. delay probability of 4.57%. Correspondingly, the probability of punctually carrying out a takeoff amounts to 95.43%.

As can be seen, the flight control system is the cause for, all told, 73 of every 3,755 delays; the relative delay frequency as a result of the flight control system amounts to $8.9 \cdot 10^{-4}$.

The most frequent cause of delay is damage to the landing gear. It causes 16.35% of all delayed takeoffs. Compared with the remaining operational equipment, the flight control system of the Boeing 707/720 is relatively reliable.

L-102 B (Sear-Siegler Corp).

The autopilot L-102 B is installed in the aircraft of the type SE 210 Caravelle. The number of premature replacements, total number of flight hours as well as removal and malfunction rates according to data of United Air Lines are indicated in Table 16. The fleet of United Air Lines comprehended in this time span 20 aircraft of the type SE 210 Caravelle. /44

There results a mean value of the malfunction rate of

$$44 \cdot 10^{-4} \quad h^{-1}$$

Accordingly, an MTBF of 227 hrs.

TABLE 15. RELATIVE FREQUENCY OF TAKEOFF DELAYS WITH AIRCRAFT OF THE TYPE BOEING 707/720 AS A OF A RESULT OF MALFUNCTIONS AFTER [86].

Assembly	Number of Delays	Delays per Takeoff
Autopilot	73	$0.89 \cdot 10^{-3}$
Airconditioning	172	2.09
Flight Data Recorder	383	4.66
Electrical System	184	2.24
Fire Protection	98	1.19
Aircraft Piloting	186	2.26
Fuel System	108	1.32
Hydraulics	297	3.61
Landing Gear	611	7.43
Engine	138	1.68
Fuel Regulator	139	1.69
Ignition	36	0.44
Air	142	1.73
Engine Supervision	49	0.60
Thrust Reversal	259	3.15
Engine Oil	197	2.40
Starter	286	3.48
Other	397	3.83
Total	3755	$45,69 \cdot 10^{-3} = 4.57\%$
Number of takeoffs	82,187	

SP-50 (Sperry) /45

Wagner [87] reports on the findings in the first year after introduction of the autopilot SP-50 of the firm Sperry in line service in 1961/62. Figure 14 shows the removal rate (upper curve line) and the malfunction (lower curve line) as a function of time. It can be seen that after a time of ca. 9 months, the removal and malfunction rates assume a constant value. These amount to:

$$\text{removal rate } E = 60 \cdot 10^{-4}$$
$$\text{malfunction rate } \lambda = 40 \cdot 10^{-4}$$

TABLE 16. REMOVAL AND MALFUNCTION RATES OF THE L-102

Time Span	Jan. 1965	Feb.	Mar.	Apr.	May	June 1965	Mean Value Jan-June 1965
Number of Premature Replacements	38	33	19	32	32	38	
Total Number of Flight Hours	3,665	3,282	3,101	3,699	3,817	3,917	
Removal Rate	104	101	61	87	84	$97 \cdot 10^{-4}$	$88 \cdot 10^{-4}$
Malfunction Rate							$44 \cdot 10^{-4}$

The ratio of premature removals to actually verified defects receeds here, as can be seen from Table 14, from an initial value 2.0 to a value of 1.5

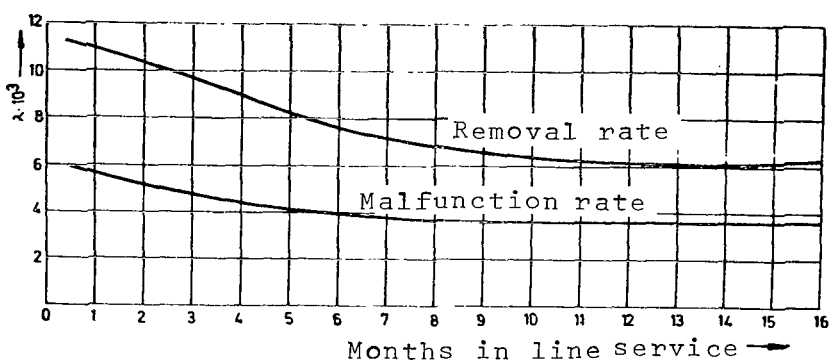


Fig. 14. Removal and Malfunction Rates of SP-50

SP-50 in Aircraft B 727 of United Air Lines /46

The autopilot SP-50 of the firm Sperry is installed in the aircraft of the Boeing 727 type. The United Air Lines fleet included 26 aircraft of this type in the time span of 1964-1965 under consideration here.

Table 17 shows the number of premature removals and the corresponding number of flight hours as well as the removal and malfunction rates ascertained from them.

TABLE 17. REMOVAL RATES OF THE SP-50

Time Span	July 1964	Aug. Sept.	Oct. Nov.	Dec. Jan.	Feb. Mar.	Apr. May June 1965
Premature Replacements	41	34 40	38 47	52 48	33 30	50 46 35
Total Number of Flight Hours	3,581	4,002 3,958	4,627 5,026	5,377 5,235	5,095 5,660	5,984 6,945 7,518
Removal Rate	114	85 101	82 89	97 92	65 53	83 67 47

There results, as a mean value for the time span of 1 year, a removal rate of $81.3 \cdot 10^{-4}$ and, from that, a removal rate of

$$40.6 \cdot 10^{-4} \quad h^{-1}$$

Correspondingly, an MTBF of 247 h.

Fourth Generation

Flight Control System of the VC-10(Elliot Bros.) /47

The evaluation of data of the British commercial airline BOAC[6] which has in service a fleet of 20 aircraft of the type VC-10 in this time span yielded the results reconstructed in Table 18 for the entire flight control system. A breakdown according to assemblies is given in Table 19.

2.2.2. COMPARATIVE CONSIDERATION OF THE MALFUNCTION RATES OF FLIGHT CONTROL SYSTEMS

The malfunction rates of the considered autopilots are compiled in Table 20.

As one sees, the highest malfunction rate is that of the VC-10 pilot of Elliot. This is understandable since the system consists of two complete autopilots which must have twice as many assemblies resp. constructional units as the simple systems of the third generation. The smallest values are shown by the system SEP-4 (Smiths).

[6] Accommodatingly placed at our disposal upon request.

TABLE 18. REMOVAL RATES AND MEAN MALFUNCTION RATE OF THE AUTOPILOT OF THE VC-10 (ELLIOT) /47

Time Span	1.4.- 30.4.	1.5.- 28.5.	29.5.- 25.6.	26.6- 23.7.	24.7.- 20.8.	21.8.- 17.9.	1.4.- 17.9.1966
Number of Premature Replacements	63	55	61	80	68	69	396
Number of Flight Hours	6,551	6,276	6,276	6,107	6,421	6,226	37,857
Removal Rate $E \cdot 10^6$	9,616	8,736	9,719	13,100	10,590	11,080	$10,460 \cdot 10^{-6}$
Mean Malfunction Rate (at 54.7% actual defects)							$5,721 \cdot 10^{-6}$

TABLE 20. REMOVAL AND MALFUNCTION RATES OF THE INVESTIGATED FLIGHT CONTROL SYSTEMS

	Autopilots	Manufacturer	Removal Rate $E \cdot 10^6\ h^{-1}$	Malfunction Rate $\lambda \cdot 10^6\ h^{-1}$	Year	Source
2nd Generation	A - 12 PB - 10	Sperry Bendix	12,000	6,000 +)	1947	UAL
	A - 12 PB-10	Sperry Bendix	4,000	2,000 +)	1951	UAL
	PB-10A	Bendix	6,700	2,990	1960	DLH
3rd Gen.	SEP-4	Smiths	--	1,740	1961	BEA
	SP-30	Sperry	7,000	3,500 *	1965	UAL
	PB-20D	Bendix	--	4,496	1964	AF
	PB-20D	Bendix	10,000	4,630	1965	UAL
	L-102	Lear	8,800	4,400 *	1965	UAL
4th Gen.	SP-50	Sperry	6,000	3,800	1962	Sperry
	SP-50	Sperry	8,130	4,060 *	1965	UAL
	VC-10 AFCS	Elliot	10,460	5,721	1966	BOAC

* Malfunction rate calculated from removal rate.

TABLE 19. REMOVAL AND MALFUNCTION RATE OF THE ASSEMBLIES OF THE VC-10 AUTOPILOT

Time Span		1.4.66 30.4.66	1.5.66 28.5.66	29.5.66 25.6.66	26.6.66 23.7.66	24.7.66 20.8.66	21.8.66 17.9.66	1.4.66 17.9.66	Removal Rate Per Assembly	Quotient of the Actually Verified Defects (%)	Malfunction Rate Per Assembly
Number of Flight Hours		6 551	6 276	6 276	6 107	6 421	6 226	37 857			
Designation of Assembly	No. of Installed Assemblies per Aircraft										
Comparison Monitor	2	2	0	1	3	2	2	10	132	10	13,2
Yaw Rate Platform	2	2	2	2	3	1	0	10	132	100	132
Standby Yaw Damper	1	0	1	3	0	0	0	4	106	60	64
Transmitter 3 Axis Rate	2	4	3	9	7	10	5	38	502	55	276
Dual Controller	1	9	4	2	9	5	9	38	1 004	85	851
Accessory Unit	2	2	1	2	0	0	1	6	79	80	63
Vertical Gyro Comparison	2	4	10	5	9	5	4	37	488	82	402
Power Junction Box	2	4	3	6	2	4	0	19	251	61	153
Comparison Air Date Sensor	2	1	0	0	0	1	1	3	39	0	0
Triple Indicator	1	0	1	0	1	0	0	2	53	100	53
Longitude Amplifier & Computer	2	8	3	10	13	5	13	52	687	66	453
Lateral Amplifier & Computer	2	9	17	13	14	20	13	86	1 136	39	443
Air Data Sensor	2	14	9	6	15	15	15	74	977	72	704
Dual Actuator Throttle	1	3	1	1	1	0	4	10	264	70	185
Auto Throttle Controller	1	1	0	0	1	0	2	4	106	50	53
Position Transmitter	8	0	0	0	0	0	0	0	--	0	--
Dynamic Vertical Sensor	2	0	0	1	2	0	0	3	39	0	--
Total No. of Premature Replacements		63	55	61	80	68	69	396		54,7 %	
Removal Rate · 10^6		9 616	8 763	9 716	13 100	10 590	11 080	10 460			

2.3. Malfunction Rates of the Components of Flight Control Systems

2.3.1. ASSEMBLIES

2.3.1.1. Sensors

2.3.1.1.1. Sensors of the Stabilizing and Damping Gyro System

2.3.1.1.1.1. Position Gyros

The simplest form of flight control takes place by means of measurements of the course angle of the aircraft with the help of free gyros, which give off a signal proportional to the angle of course deviation from the prescribed flight position around the axis in question. If the angle measurement is carried out around the vertical-(course- yaw-) axis, then one speaks of directional gyroscopes. The angle of course deviation with respect to the longitudinal-(roll-) axis and transverse-(pitch-) axis are measured by means of vertical, (horizon, attitude) gyros. /50

Electrically driven free gyros are electro-mechanical assemblies which are subject to statistically distributed accidental malfunctions, as well as to wear.

Pneumatically driven free gyros are no longer used today in flight control systems.

Theoretical consideration of the reliability of position gyros.

According to reference [88], two different defect types can be distinguished in the case of free gyros as a result of their construction: electrical and mechanical defects.

Electrical Defects:

Since the wrappings of the gyro motor and the Syndros consist of insulated wire on an iron or ferrite core, the same considerations as for transformers can be made for the electrical malfunctions. Especially, the malfunction rate for transmitters and for transformers hold true for the electrical defects [88].

Mechanical defects are, in general, connected with the ball-bearings and brushes and can be regarded as the effects of friction, which are dependent on number of revolutions. The total malfunction rate of a rotating electromechanical part is thus comprised of an electrical portion, which can be regarded as an accidental malfunction rate, and a mechanical portion. /51

Figure 15 shows the mechanical malfunction rate for the electrical motors as a function of number of revolutions. The number of

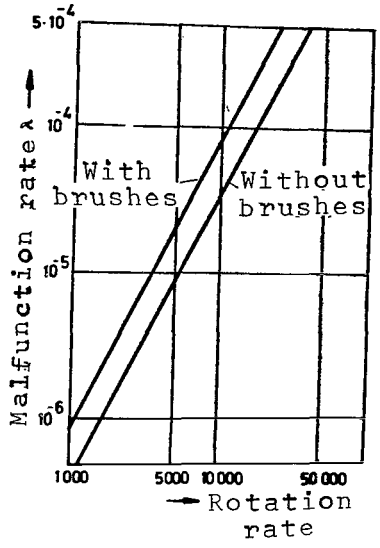


Fig. 15. Mechanical Malfunction Rate of Motors as a Function of Their Operational Rate of Revolution After [88], p. 145.

revolutions of the brushless 3-phase 400 Hz (Asynchronous) short circuited rotor motors employed in gyros amounts to 22000 rpm (400 Hz), so that a malfunction rate of

$$\lambda = 150 \cdot 10^{-6} \quad h^{-1}$$

would have to be assumed for gyro motors.

/52

Estimation of the malfunction rate of their constructional units: a free gyro consists of a number of individual parts [Translator's note - Error in sentence, not translatable]. It is therefore permissible to neglect the malfunction rates of these parts in an estimation.

The movable parts present are 6 ball-bearings, 2 electrical motors and 1 synchro.

The malfunction rates of these parts amount to, according to Earles and Eddins [89, 90], as mean values of the various measurements:

Ball-bearings	=	$0.8 \cdot 10^{-6}$ h^{-1}	6 = 4.8
Electromotor	=	5.2	2 = 10.4
Synchro	=	1.1	1 = 1.1
			λ = 16.3

If malfunctions of these parts can be regarded as independent of one another, there results through addition of the individual rates a total malfunction rate of

$$\lambda = 16.3 \cdot 10^{-6} \quad h^{-1}$$

This estimated value agrees well with the values for the gyros of Earles and Eddins [89, 90]. There, the following malfunction rates λ and mean life span m are indicated for free gyros.

TABLE 21. MALFUNCTION RATE OF FREE GYROS AFTER [89,90]

	Lower limit	Mean Values	Upper Limit
λ [h $^{-1}$]	$2.5\ 10^{-6}$	$10 \cdot 10^{-6}$	$25 \cdot 10^{-6}$
m [h]	200	1 000	2 000

Malfunction Rates and Reliability of Gyros and Gyro Motors of Honeywell /53

Comprehensive investigations on the life span of gyros and gyro motors have been undertaken by the firm Honeywell, on which a report is made by L.A. Weaver and M.P. Smith in [91]. It was determined there that a mixed Weibull-distribution is applicable for the discription of the malfunction behavior.

A report is made in one example on a life span test of 46 gyro motors. The rotors and frames were hermetically enclosed and were operated in an oil bath at temperatures which simulated normal operational and environmental conditions.

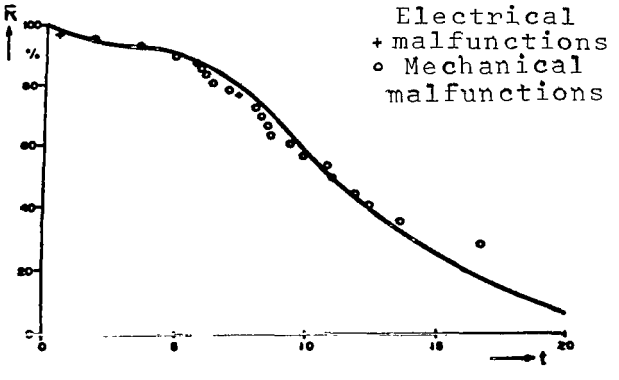


Fig. 16. Survival Probability (Reliability) of Gyro Motors as a Function of Time From [91].

Figure 16 shows the survival probability (reliability) as a function of time. The life span (test time) is plotted as the abscissa in arbitrary units, since the exact data are subject to classification. Reliability is plotted as the ordinate. Noteworthy in this curve is that only two malfunction occured as a consequence of electrical defects, all other defects are mechanical.

Only the total malfunctions were considered in this test, de- /54
terioration of operability and other properties, such as moments which can cause an increased drift, were not evaluated as defects. The malfunction of time can be seen from the data of Figure 17.

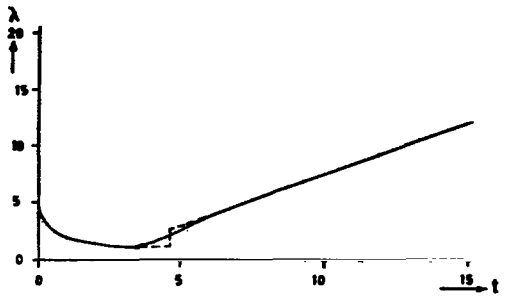


Fig. 17. Malfunction Rate of Gyro Motors as a Function of Time (Arbitrary Units) from [91].

The course of this curve has an approximately "bathtub" shape; however, no larger range results in that the malfunction rate maintains a constant value. A mixed Weibull-distribution is suitable for the description of the malfunction behavior.

Malfunction Rates of Gyros in Commercial Use

Vertical Gyro of the Autopilot PB-10A (Bendix)

An evaluation of the statistics [84] (German Lufthansa) yielded that the vertical gyro is participant with 5.95% of all malfunctions in the flight control system PB-10A. The malfunction rate amounted to within in one year with, all told, 43,469 block to block hours.

$$\lambda = 230 \cdot 10^{-6}$$

The here observed defects can be broken down in the following /55 way:

1.	Damage to bearings	20%
2.	Damage to supports	20%
3.	Not specified in more detail	60%

Vertical Gyros of the Autopilot PB-20 (Bendix)

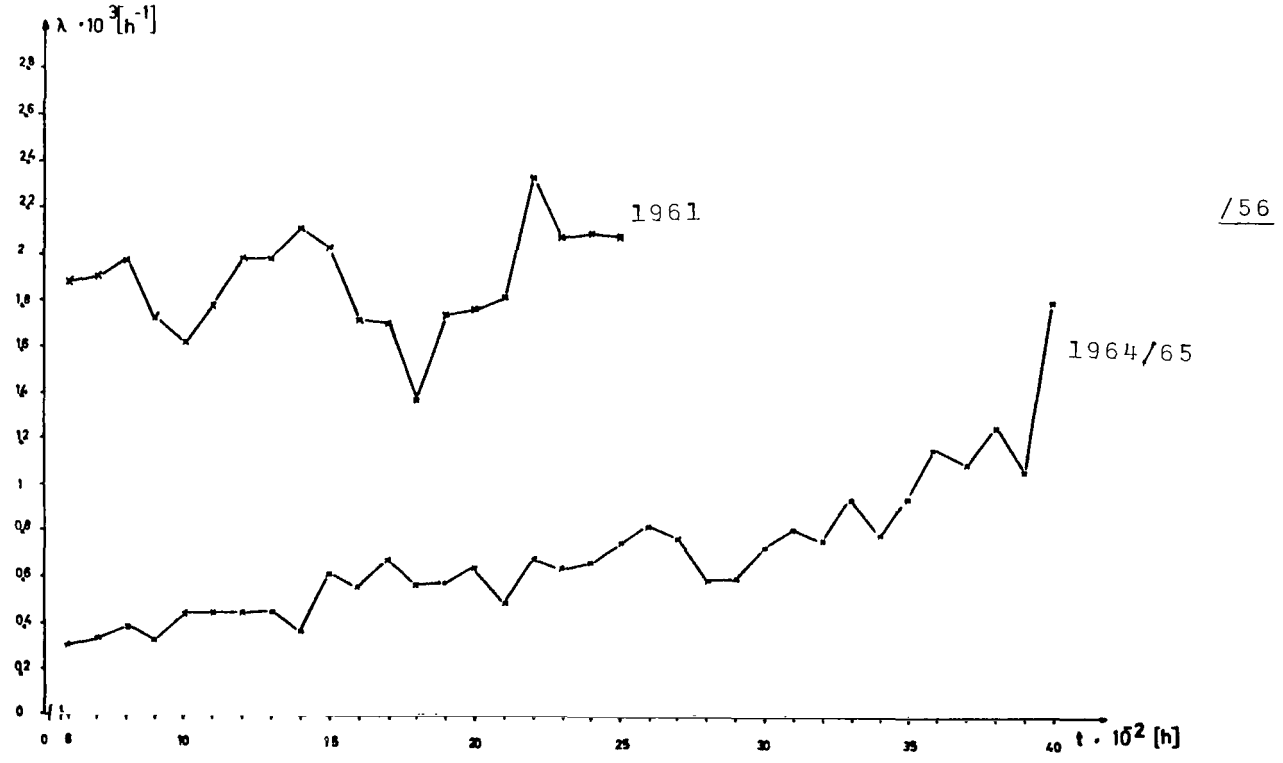
Air France determined the actual errors, reconstructed in Table 22, of the vertical gyros of the PB-20 D flight control system (Bendix), which is installed in the Boeing 707 fleet (24 aircraft) of Air France. The data concerned vertical gyros Bendix type 15 852.

The MTBF was calculated here as the quotient of the hours in operation and number of occurring errors.

The considerable lowering of the malfunction rate in the year 1964 as opposed to 1961 is note worthy. That might be the result of improved manufacturing techniques of the newer gyros on the side of the producer and of an improved maintenance on the side of the company. The dependence of the malfunction rate on operational time is shown by Figure 18.

TABLE 22. MALFUNCTION RATE OF THE VERTICAL GYRO BENDIX TYPE 15 825 (PB 20D)

Year	No. of Defects	No. of Hours in Operation	MTBF [h]	Malfunction Rate $\cdot 10^6$
1961/62	124	65 100	525	1905
1964	62	103 025	1662	602



/56

Fig. 18. Malfunction Rates of the Vertical Gyros (1961) and (1964/65)

The reliability of the vertical gyros was calculated as the relative frequency of the gyros still operable at the point of time in question to the total number of those in operation

$$R = \frac{N_{ü}}{N_o}$$

and is represented in Figure 19 as a function of operational time. /57

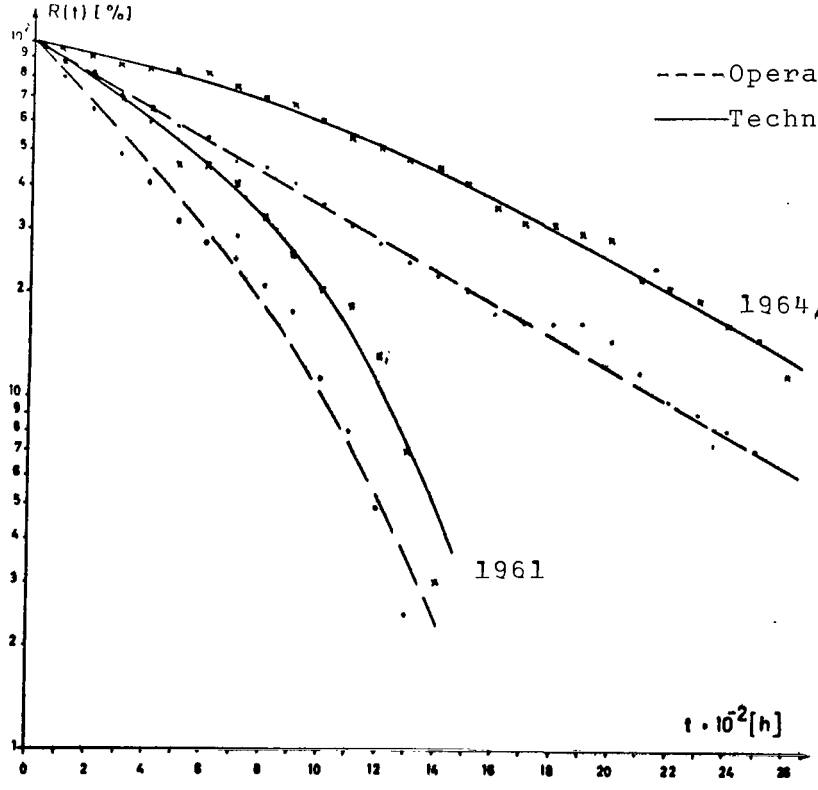
Distinguished here were also:

1. Operational reliability R_{op}: defined as malfunction, any not planned premature removal of the gyros.
2. Technical Reliability R_T: malfunction defined as the actual occurence of the defect which makes the gyro inoperable.

Since the curve of the operational reliability runs lower than that of the "technical reliability", this means that gyros are also more frequently exchanged when not planned although they are still, technically, in good condition. The ratio d also amounts here to $d \approx 2$. If a constant malfunction rate λ were the case for the gyros, a straight line would have to result in the logarithmic presentation, since (after 4.1)

$$\ln R = -\lambda t$$

However, this is apparently not the case, as can be seen from Figure 18. Figure 18 shows a gradient tendency of the malfunction rate with time, the special characteristic of parts which are subject to wear.



/58

Fig. 19. Reliability of Vertical Gyros as a Function of Operational Time 1961 and 1964/65

Vertical Gyros in Boeing B 720 and B 727

For the vertical gyro of Bendix of the autopilot PB-20 (Report time span March, April, May 1965) there results with 25,495 flight hours a malfunction rate of /59

$$\lambda = 630 \cdot 10^{-6}$$

with a number of 32 actual defects out of 60 premature replacements.

The vertical gyro of the aircraft B 727 showed during the same time a malfunction rate of

$$\lambda = 620 \cdot 10^{-6}$$

Combined assembly vertical and directional gyro of the aircraft SE 210 (Caravelle).

There results from the data of the UAL for this assembly in the time span March-May 1965 with 11,117 flight hours a malfunction rate of

$$\lambda = 1{,}650 \cdot 10^{-6}$$

Vertical Gyro of the Autopilot MH 123 B

Honeywell [92] used in the hover autopilot MH 123 B for the vertical take-off aircraft VJ 101 C of the developmental group South (EWR) a combination of vertical gyros of the type GG 53 A4, for which, in each case, a malfunction rate is assumed of

$$\lambda = 2{,}460 \cdot 10^{-6}$$

This assumption is based on findings which were obtained in operation with, all told, 2,200,000 operational hours on the vertical gyro of the type GG 53E in the Mercury program. There, a malfunction rate was observed of

$$\lambda = 3{,}630 \cdot 10^{-6}$$

In the case of this comparatively high malfunction rate, the high environmental load (shock and vibration) must be considered in installation on board an aircraft. According to Earles & Eddins [89, 90], this malfunction rate is higher by the factor 14 than in /60 the case of a comparable installation on board an aircraft, so that the following malfunction rates would result under consideration of

this factor

$$\lambda = \frac{2460}{14} = 175 \cdot 10^{-6}$$

and

$$\lambda = \frac{3630}{14} = 260 \cdot 10^{-6}$$

Gyros of the Inertial Navigational System LN-3 (Litton).

The free gyros of the stabilized platform of the LN-3 inertial navigational system (Litton) have an MTBF of 10^3 hours[7]. That would correspond to a malfunction rate of

$$\lambda = 1000 \cdot 10^{-6}$$

A summarizing survey of the malfunction rate of vertical gyros and position gyros is given in Table 23.

If one disregards the extremely high values of the Honeywell gyros used in rockets as well as the older values of the Bendix vertical gyro, the values of the SP-50 and PB-20 can be used as a basis as typical values for the malfunction rate of vertical gyros of flight control systems according to the present state. A typical malfunction rate seems to be a value of

$$\lambda = 500 \cdot 10^{-6}$$

2.3.1.1.1.2. Stabilized Platforms

Stabilized Platforms of the Inertial Navigational System SGN-10 (Sperry)

Sperry [93] gives the following values for the stabilized platform and the amplifier unit belonging to it as well as the further assemblies of the system based on findings with a similar system (B-58 Navigation system) and 750,000 operational hours of the gyros of its compass gyro systems.

Flight Position and Course Reference System ASN-50, To Stabilized Platform 2171 (Lear-Siegler)

Lear-Siegler indicates, based on the findings in a military aircraft F-105 (Thunderchief), McDonell Phantom F-4C of the USAF, the values reconstructed in Table 25, for malfunction rates and MTBF of the system AN/ASN-50 under operative conditions [94].

Stabilized Platform of the Firm Nortronics

Nortronics [94] indicates for the inertial navigational system NIS-105 the estimated values reconstructed in Table 26. Differing

[7] According to data of the manufacturer.

TABLE 23. MALFUNCTION RATES OF POSITION GYROS

Designation	Type	Manufacturer	Autopilot	Aircraft	Source	Year	Malfunction Rate
Vertical Gyros	15825	Bendix	PB-20 D	B 707	AF	1961	$1905 \cdot 10^{-6}$
"	"	"	"	"	"	1964	602
"	---	"	PB-10A	Viscount, Constellation	DLH	1961	230
"	GG53A4	Honeywell	---	Mercury	Honeywell		2460++)
"	GG53E	"	---	Mercury	"		3630++)
Position Gyros	---	Litton	LN-3+)	F 104 G	Litton	1964	1000
Vertical Gyros	15825	Bendix	PB-20 D	B 720	UAL	1965	630
"	---	Sperry	SP-50	B 727	UAL	1965	620
"	---	Elliot	VC-10	VC-10	BOAC	1966	402

+) Inertial Systems

++) Used in rockets/satellites

TABLE 24. MALFUNCTION RATES AND MTBF OF THE INERTIAL NAVIGATIONAL SYSTEM SPERRY SGN-10 AFTER [93] /62

Assembly	Malfunction rate $\lambda \cdot 10^6$	MTBF [h]
Stabilized Platform	654	1530
Amplifier Unit	407	2460
Store	80	12500
Data Processing	193	5170
Indication	89	11200
Control Unit	2	447000
Total	1425	702
Stabilized Platform Amplifier Unit	1061	942

TABLE 25. MALFUNCTION RATES MTBF OF THE FLIGHT POSITION- AND COURSE REFERENCE SYSTEM ASN-50 (LEAR SIEGLER) [94] /63

Assembly	Malfunction rate $\lambda \cdot 10^6$	MTBF [h]
Stabilized Platform	1,000 - 1,430	700 - 1,000
Amplifier and Power Supply Unit	310 - 450	2,200 - 3,200
Compass-Adapter	410 - 1,130	880 - 2,400
Compass-Control Unit	40 - 80	12,000 - 24,000
Switch Rate Gyros	50	20,000
Total	1,850 - 3,150	317 - 540

values hold true in the use of gas mounted gyros of tye type GI-M 1 or in the use of bearing mounted gyros of tye type GI-K 7 in the stabilized platform.

If one neglects the values obtained as a result of theoretically analyses of the Nortronics platform, which, as a frameless platform, represents a advanced technology, there appears as typical a value, appropriate to the present state of technology of the mal- /64

TABLE 26. MALFUNCTION RATE AND MTBF OF THE INERTIAL NAVIGATIONAL SYSTEM NIS-105 (NORTRONICS) [95]

Assembly	Malfunction rate $\lambda \cdot 10^6$	MTBF [h]
Platform (gas mounted gyro)	417	2,400
Platform (bearing mounted gyro)	726	1,300
Digital Computer	210	4,700
Control unit and Indication	158	6,250

A summarizing survey is given in Table 27.

TABLE 27. MALFUNCTION RATES OF STABILIZED PLATFORMS

Designation	Type	Manufacturer	Source	Year	Malfunction rate $\lambda \cdot 10^6 [h^{-1}]$	Comments
Position References		Lear	UAL	1965	1,650	-------
Stabilized Platform		Sperry	Sperry	1965	1,061	Inertial navigational system SGN-10
Stabilized Platform	2171	Lear-Siegler	Lear-Siegler	1963	1,880	AN/ ASN-50
Stabilized Platform		Nor-tronics	Nor-tronics	1965	417	Gas mounted gyros
Stabilized Platform		Nor-tronics	Nor-tronics	1965	762	Bearing mounted gyros

function rate of stabilized platforms of

$$\lambda = 1{,}500 \cdot 10^{-6} \quad h^{-1}$$

2.3.1.1.1.3. Rate Gyros

Rate gyros belong to the essential sensors in flight control systems. There are various manifestations which give off, in each case according to construction type, an integrated or differential signal proportional to the angular velocity around its input axis (P, I, D-rate gyros). Realizations and function will now be considered here in more detail, reference will be made to the specialized literature and [96]. /65

Gyro Unit of the SEP-4

The following malfunction rate resulted for gyro units in the span from April 1961 to March 1962 in the flight operations of the BEA

$$\lambda = 350 \cdot 10^{-6}$$

The gyro unit is a sensor for the flight control system SEP-4 (Smith Aviation Division) and is installed in the fleet of, all told, 59 aircraft of the type V0814 (Viscount) of the British European Airways. The malfunction rate was calculated in the time span of the report with, all told, 83,880 flight hours from the actually ascertained defects.

The gyro unit contains three rate gyros. There results for a rate gyro, proportionally, a malfunction rate of

$$\lambda = 116 \cdot 10^{-6}$$

There resulted for the time span July 1961 to June 1962 with, all told, 34,141 flight hours in 13 aircraft of the type Comet IV of the same airline, for the gyro unit of the flight control system SEP-4 a malfunction rate of

$$\lambda = 220 \cdot 10^{-6}$$

Correspondingly, one obtains for a rate gyro the value

$$\lambda = 72 \cdot 10^{-6}$$

More recent statistics (Smiths/-BEA) yield a value of

$$\lambda = 50 \cdot 10^{-6}$$

Rate Gyros of the PB-10A System

The rate gyro belonging to the flight control system was one of the most frequent causes of defects (28%) in the entire system. The malfunction rate of this type resulted in, after [84] /66

$$\lambda = 1{,}081 \cdot 10^{-6}$$

The predominant part of the malfunctions (89%) was caused by a contamination of the pneumatic damping.

Malfunction Rate of Rate Gyros According to AVCO

A very comprehensive collection of malfunction rates has been set up by Earles and Eddins (AVCO Corp) [89, 90]. Malfunction rates and MTBF of rate gyros are numbered there with the values reconstructed in Table 28.

TABLE 28. MALFUNCTION RATES AND MTBF OF RATE GYROS AFTER [89, 90]

	Lower Limit	Mean Value	Upper Limit
$\lambda \cdot 10^6$ h^{-1}	2.8	7.5	15.5
MTBF h	100	2,000	40,000

The mean value of the life span of rate gyros is twice as high as that of free gyros, according to Earles and Eddins.

The above indicated malfunction rates appear relatively low. Earles and Eddins indicate, however, reproductive factors, in each case according to position of installation (e.g. aircraft during flight). The factor 2 must be placed with application in aircraft during flight, so that one must figure on a mean value of

$$\lambda = 15 \cdot 10^{-6}$$

Rate Gyros of Honeywell

The following data are available for rate gyros of the type "Golden Gnat" of the firm Honeywell [92]. During a total operational time of 175,000 hours, 8 malfunctions were recorded. Thus, a malfunction rate is yielded for this type of /67

$$\lambda = 45.7 \cdot 10^{-6}$$

These data were obtained from operations in flight control systems for the F-104 (autopilot MH-97) and the adaptive flight control system of the experimental aircraft X-15. Report was made by [91] on an investigation of miniaturized integrating rate gyros of Honeywell by Weaver and Smiths in example 11. These gyros are conceptualized for application in an inertial platform.

The results of the life span tests of Honeywell are presented in Figure 20.

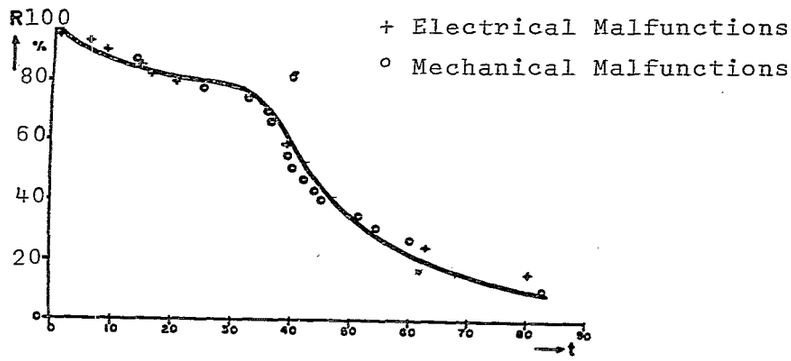


Fig. 20. Reliability of Rate Gyros from [91]

The course of the malfunction rate resulting from this is re- /68
constructed in Figure 21.

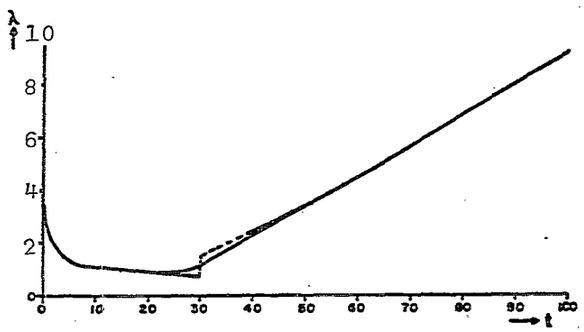


Fig. 21. Malfunction Rate of Rate Gyros as a Function of Time (Arbitrary Unit) from [91]

It can be seen from Figure 21 that there is a range of life span in which the malfunction rate has an approximately constant value; however, it increased toward larger times. This behavior was explained through wear.

Rate Gyro Unit of the PB-20 D

United Air Lines (UAL) determined for the assembly "Three-Axes Rate Control", which contains three rate gyros, the premature replacements reconstructed in Table 29 in, all told, 29 aircraft of the type Boeing 720.

If one again assumes the ratio of replacements and real defects with d = 2.16 and considers that the gyro unit contains three rate /69
gyros, there results a mean malfunction rate for one rate gyro

TABLE 29. PREMATURE REPLACEMENTS OF THE RATE GYRO UNIT OF THE PB-20

1964-65	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	Total
Number of Flight Hours	8,236	7,883	8,168	8,431	7,595	8,418	8,348	8,129	8,511	73,719
Premature Replacement	1	1	3	3	3	1	2	5	3	22
Malfunction Rate										$297 \cdot 10^{-6}$

$$\lambda = 45.8 \cdot 10^{-6}$$

Rate Gyros of the L-102 B

There resulted for the rate gyro unit (three rate gyros) of the autopilot Lear-102 B of the aircraft type SE 210 (Caravelle) according to data of United Air Lines a mean removal rate of $5.88 \cdot 10^{-4}$, correspondingly, a malfunction rate of

$$\lambda = 272 \cdot 10^{-6}$$

there results proportionately per rate gyro

$$\lambda = 90 \cdot 10^{-6}$$

Rate Gyro Unit of the Autopilot for the VC-10 (Elliot)

There results according to data of BOAC for the rate gyro unit a malfunction rate of

$$\lambda = 276 \cdot 10^{-6} \quad h^{-1}$$

Proportionately, there results per rate gyro

$$\lambda = 92 \cdot 10^{-6} \quad h^{-1}$$

The malfunction rates of rate gyros are summarized in Table 30.

If one neglects the extraordinarily poor values of the PB-10 /70
Rate gyro, then a value of

TABLE 30. MALFUNCTION RATES OF RATE GYROS

Designation	Manufacturer	Autopilot	Aircraft	Source	Year	Malfunction Rate $\lambda \cdot 10^6$
Rate Gyro	Smiths	SEP-4	Viscount	BEA	1962	116
"	Smiths	SEP-4	Comet	BEA	1962	73
"	Smiths	SEP-5	Trident	BEA	1965	50
"	Bendix	PB-10A	Constel-lation, Viscount	DLH	1961	1,081
"	Honey-well	MH-97	F-104-G, X-15	Honey-well	1964	46
"	Lear-Siegler	L-102B	SE-210 (Caravelle)	UAL	1965	90
"	Bendix	PB-20D	B 720	UAL	1965	45
"		VC-10	VC-10	BOAC	1966	92

$$\lambda = 70 \cdot 10^{-6} \quad h^{-1}$$

appears, as the mean value of the remaining malfunction rates, to be a typical value.

2.3.1.1.1.4. Accelerometers

There are accelerometers in various forms[96]. Individually, linear control-accelerometers of the Mass-spring type are used for purposes of flight control (e.g., autopilot SP-30). However, they are not used in a majority of flight control systems for aircraft for control-technological reasons (great inertial moments of the aircraft around the main axis). An angular velocity signal, like that obtained from rate gyros, suffices for the most part for the /71
attainment of the necessary control quality. Accelerometers for the measurement of angular velocity must be found in the case of high-performance aircraft. Linear accelerometers are installed in pairs symmetrictically outside of the aircraft center of gravity and switched mutually to eliminate signals from linear accelerations of the aircraft.

Accelerometer of the SP-30 (Sperry)

In commercial service of the airlines, there resulted in the first six months of 1965 with, all told, 76,178 flight hours of the aircraft DC-8 with 22 removals of the 6 accelerometers per aircraft a replacement rate of

$$E = 48.1 \cdot 10^{-6}$$

per accelerometer. Correspondingly, one could figure on a malfunction rate of

$$\lambda = 24 \cdot 10^{-6}$$

Honeywell [92] indicates for accelerometers a malfunction rate of

$$\lambda = 80 \cdot 10^{-6}$$

Simths Aviation Division indicates a value range of

$$20 - 125 \cdot 10^{-6}$$

There can be assumed as a mean value

$$\lambda = 70 \cdot 10^{-6}$$

AVCO (Earles & Eddins [89, 90]) indicates for linear accelero-/72
meters the values reconstructed in Table 31.

TABLE 31. MALFUNCTION RATE OF ACCELEROMETERS AFTER [89, 90]

Malfunction Rates 10^6 h^{-1}		
Line Boundary Value	Mean Value	Upper Boundary Value
0.35	2.80	21.40

The malfunction rates of accelerometers are compiled in Table 32.

TABLE 32. MALFUNCTION RATE OF ACCELEROMETERS

Manufacturer	Autopilot	Aircraft	Source	Year	Malfunction Rate 10^6 h^{-1}
Sperry	SP-30	DC-8	UAL	1965	24
Honeywell	---	--	Honey-well	1962	80
Smiths	---	--	BEA	1965	70
--	---	--	AVCO	1962	21.4

could be assumed as a typical value of the malfunction rate of accelerometers

$$\lambda = 50 \cdot 10^{-6}$$

2.3.1.1.2. Bearing Sensors for the Steering Control System

/73

2.3.1.1.2.1. General Information

At this place, only the removal and malfunction rate of the sensors of the steering control system are investigated, which are generally used at this time in aeronautics. We are concerned here with a steering with respect to vertical bases, as for example, course and horizontal surface, as for example altitude of aircraft.

Used as sensors for bearings are:

magnetic field detectros, compass systems (compass bearing gyros), navigation receivers (electro-magnetic bearings) for VOR, NDB, ILS (localizer).

Barometric (aneroid) altimeters and radio altimeters as well as the modulation of the ILS glide path over a navigation receiver are used as sensors for tail-plane areas. Since the barometric altimeters are supported on static air data, they are often combined with dynamic (velocity head) air data sensors into a constructional unit air data sensor. The JAS defect signal or, correspondingly, a Mach number signal is used for the control of the angle of pitch and thus of the root resp. Mach number (alternative to altitude position).

2.3.1.1.2.2. Magnetic Field Detectors, Compass Systems

Compass System of the PB-10A (Bendix)

The compass of the PB-10A switches the compass deviation signals of the magnetic field detector after amplification in the compass amplifiers over a clutch directly onto the aeileron resp. side rudder channel of the autopilot. It is not a matter of a compass directed directional gyroscope system.

Evaluation of [84] (German Lufthansa) yielded the replacement /74 and malfunction rates reconstructed in Table 33 of the assemblies of the compass system.

TABLE 33. REPLACEMENT RATE AND MALFUNCTION RATE OF THE COMPASS SYSTEM OF THE PB-10A

Component	Number of Replacements	Number of Defects	Flight Hours	Removal Rate $E \cdot 10^6$	Malfunction Rate $\lambda \cdot 10^6$
Flux Gate Meter	27	15	43,469	621	345
Compass-Amplifier	26	20	43,469	598	460
Master Direction Indicator	25	9	43,469	575	207
Total	78	44	43,469	1,794	1,012

Earles & Eddins [89, 90] indicate for a simple magnetic compass a malfunction rate of

$$\lambda = 8.66 \cdot 10^6$$

2.3.1.1.2.3. Navigation Receiver

The evaluation of statistics of United Air Lines and BOAC (VC-10) yielded for the navigation receiver (VOR, ILS-Localizer, ILS-Glide path receiver, ADF) the removal and malfunction rates presented in Tables 34 and 35 (Time span March-May 1965).

TABLE 34. MALFUNCTION RATE OF VHF-COMM./NAV. RECEIVERS /75

Aircraft	Number of Replacements	Number of Defects	Number of Flight Hours	Removal Rate $E \cdot 10^6$	Malfunction Rate $\lambda \cdot 10^6$
DC-8	246	147	38,493	1,600	950
B 720	141	64	25,495	1,380	630
B 727	164	90	18,589	2,210	1,210
SE 210 (Caravelle)	112	74	11,217	2,500	1,650
VC-10	46	21	37,857	1,215	540
VC-10+)	30	20	37,857	779	532

+) Glide Path Receiver.

TABLE 35. MALFUNCTION RATES OF NDB-RECEIVERS (ADF)

Aircraft	Number of Replacements	Number of Defects	Number of Flight Hours	Removal Rate $E \cdot 10^6$	Malfunction Rate $\lambda \cdot 10^6$
DC-8	106	61	38,493	1,380	790
B 720	62	38	25,495	1,220	750

NDB receivers are not suitable for an automatic flight piloting because of too-slight accuracy of the azimuthal information.

A malfunction rate of

$$\lambda = 1{,}000 \cdot 10^{-6} \quad h^{-1}$$

could be assumed for VHF receivers as a mean value of Table 34.

2.3.1.1.2.4. Air Data Sensors

Altitude Sensors of the PB-10A

/76

The altitude control of the PB-10A consists of an aneroid which is connected to a syncro through a magnetic clutch.

It can be seen from the report of German Lufthansa [84] that the altitude control unit is involved in 11.9% of all occurring malfunctions of the flight control system. The malfunction rate of this unit results at

$$\lambda = 460 \cdot 10^{-6}$$

The damage of, all told, 17 defects distributed itself over the following constructional units (Table 36):

TABLE 36. DISTRIBUTION OF DEFECTS OF THE THE ALTITUDE CONTROL PB-10A AFTER [84]

Constructional Units	No. of Cases of Damage
Mounting	6
Clutch	5
Syncro	2
Other	4
Total	17

Air-Data-Computer of the SP-30

The air-data-computer consists of an altitude control, a velocity head switch and further electrical and mechanical constructional units. Input variables are Pitot and Static pressure; output variables are electrical signal for altitude maintenance as well as a signal of the velocity head switch, which is proportional to three velocity ranges, to the adaptive alteration of degree of amplification of the main amplifier.

There results from the data of United Air Lines for this assembly, of which 2 per aircraft (DC 8), a malfunction rate of

$$\lambda = 30.3 \cdot 10^{-6}$$

Combined Barometric Altitude Control and Air Data Sensor of the PB-20D

The air data sensor assembly serves as a sensor for two electrical signals which are proportional to pressure level and velocity head. The unit consists of two pressure boxes and the electrical pick-ups and servos. /77

Air France determined the following malfunctions in operation:

TABLE 37. MALFUNCTION RATE OF THE AIR DATA SENSOR OF THE PB-20D (BENDIX)

Year	No. of Actual Defects	No. of Flight Hours	Malfunction Rate $\lambda \cdot 10^6$	MTBF [h]
1963	52	52575	990	1010
1964	43	65250	663	1510

The malfunction rates indicated in Table 37 are mean values. Figure 22 and 23 show a more exact course of the malfunction rates as a function of time

/78

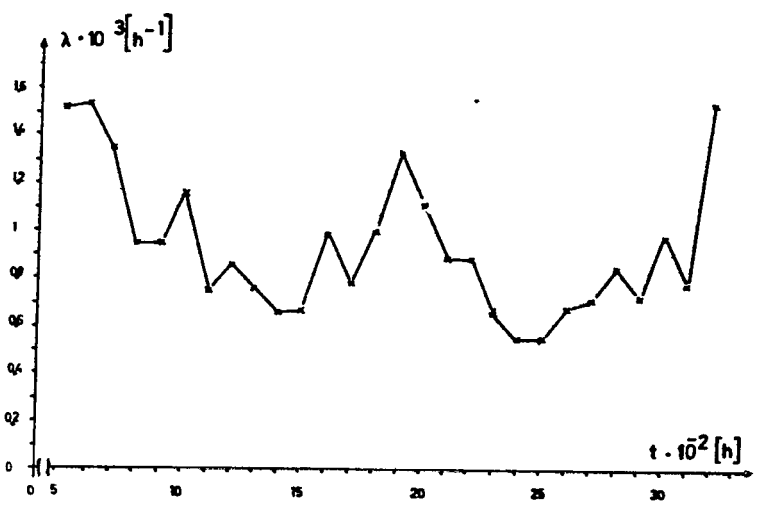


Fig. 22. Malfunction Rate of The Air-Data-Sensor (PB-20) as a Function of Operational Time (1963)

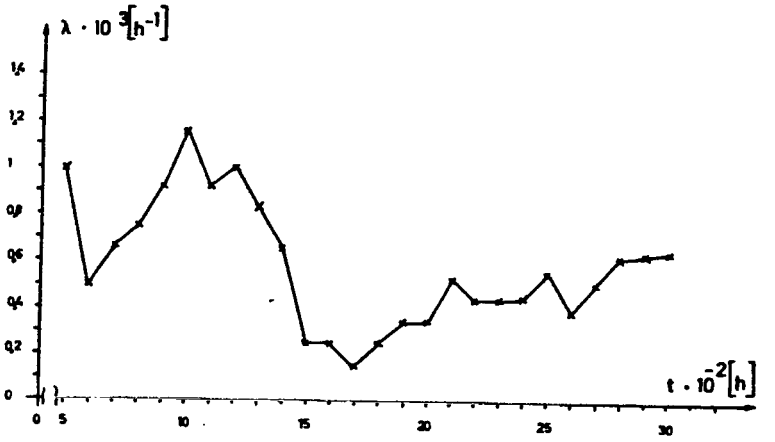


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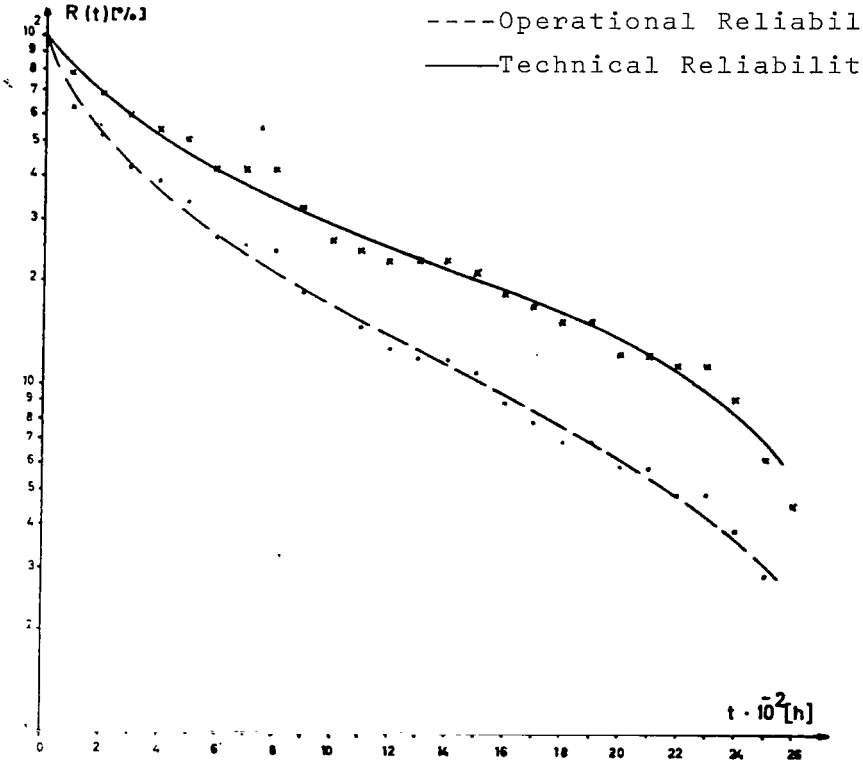
Fig. 23. Malfunction Rate of the Air-Data Sensor as a Function of Operational Time (1964)



/80

Fig. 24. Reliability as a Function of Operational Time (1963)

/81

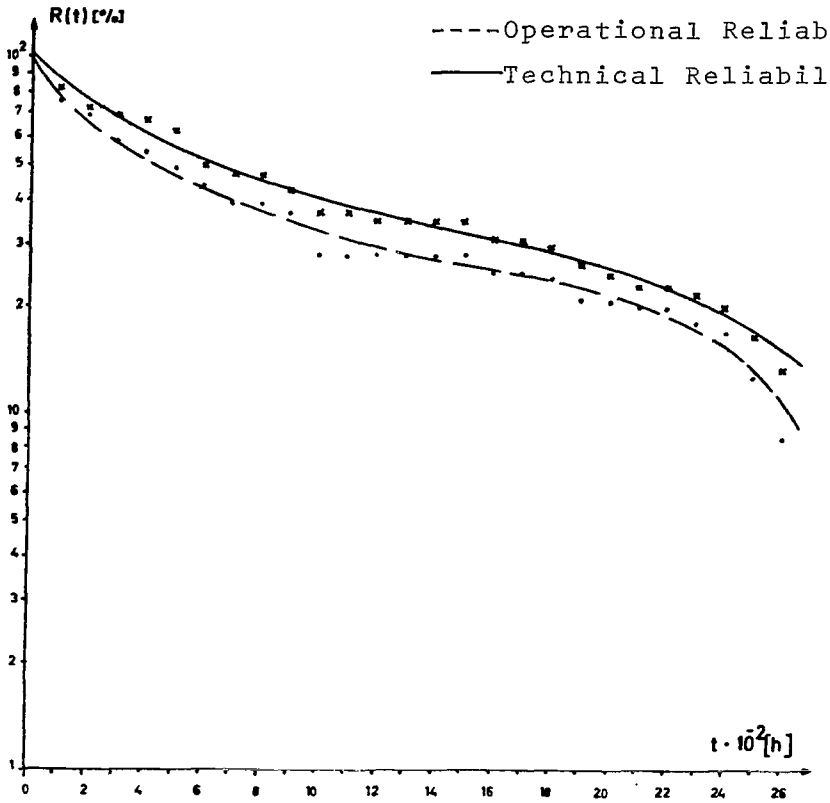


Fig. 25. Reliability as a Function of Operational Time (1964)

The reliability as a function of time of the assembly air-data-sensor is presented in Figures 24 and 25. The ratio of operational/82 reliability to technical reliability also amounts here to 0.5.

Noteworthy is that the probability of reaching 2000 h amounted to 13% in 1963. In 1964, however, 25%.

The following removal rates E were able to be determined from statistics of United Air Lines for the air-data-sensor of the PB-20 of the Boeing 720

$$E = 717 \cdot 10^{-6}$$

One obtains from this division by the factor d = 2.16 the malfunction rate

$$\lambda = 332 \cdot 10^{-6}$$

If one compares this value with the results from the statistics of Air France, where a value of $\lambda = 663 \cdot 10^{-6}$ resp. $\lambda = 990 \cdot 10^{-6}$ result-

ed for the aircraft design B 707 for the same assembly, then the above found value is smaller by the factor two to three. The reason for this could lie in the essentially different operational profile of the medium range aircraft B 720 as opposed to the long range version B 707.

Air-Data-Sensor of the SP-50 B (B 727)

A mean removal rate of $762 \cdot 10^{-6}$ occurred in the time span July 1964 - July 1965 in the fleet of United Air Lines in the air-data-sensor of the SP-50, corresponding to the malfunction rate of

$$\lambda = 353 \cdot 10^{-6}$$

Altitude Control of the L 102 B (Caravelle Autopilot)

A removal rate of $11.77 \cdot 10^{-4}$ resulted in the time span Jan.-July, 1965 with, all told, 22,090 flight hours in the case of United Air Lines for the barometric altitude control unit, corresponding to a malfunction rate of

$$\lambda = 544 \cdot 10^{-6}$$

Pressure Unit of the SEP-4 (Comet IV Autopilot)

The BEA ascertained from July 1961 to July 1961 with, all told, 34,141 flight hours of the fleet of 13 aircraft of the type Comet /83 a malfunction rate of

$$\lambda = 490 \cdot 10^{-6}$$

The malfunction rates of air-data-sensors are compiled in Table 38.

The mean values of these malfunction rates of the combined altitude and velocity head sensor hardly distinguished itself from that of the simple altitude sensors.

2.3.1.2. Computer - Amplifier

2.3.1.2.1. General Information

The expansions of the functions of flight control systems and /84 greater demands of the control quality were only possible, compared with the first generation, by means of the application of electronic computer-amplifiers. Corresponding to the state of technology, it was, to begin with, tube apparatus in the control systems of the second generations (PB-10, A-12, SEP-2). The reliability of the electronic assemblies was, to begin with, very unsatisfactory (Bazowsky [75]). Only with the introduction of semiconductor constructional units especially transitors, around 1955, into the flight

TABLE 38. MALFUNCTION RATES OF AIR-DATA-SENSORS

Manufacturer	Autopilot	Aircraft	Source	Year	Malfunction Rate $\lambda \cdot 10^6 h^{-1}$	Remarks
Sperry	SP-30	DC-8	UAL	1965	30	Combined altitude and pressure head sensor (Pilot-Static)
Bendix	PB-20 D	B 707	AF	1963	990	
Bendix	PB-20 D	B 707	AF	1964	663	
Bendix	PB-20 D	B 720	UAL	1965	332	
Sperry	SP-50	B 727	UAL	1965	353	
Lear-Siegler	L-102	SE 210	UAL	1965	544	Altitude Sensor (Static)
Smiths	SEP-4	Comet	BOAC	1962	490	
Bendix	PB-10A	V-814	DLH	1961	460	

control systems of the third generation, could the reliability of the electronics be essentially improved (Brodzik, J. [98], p. 31).

2.3.1.2.2. Malfunction Rates

Computer-Amplifier of the Autopilot PB-20 D

An evaluation of the statistics of Air France yielded for the year 1964-1965 for the computer-amplifier of the PB-20 D a mean malfunction rate of

$$\lambda = 1480 \cdot 10^{-6}$$

(84 malfunctions in 56,925 flight hours).

A more precise presentation of the temporal course of the malfunction rate is reconstructed in Figure 26. It can be seen that it is justified to calculate with a constant mean malfunction rate within the static fluctuations. The greatest and smallest of values of the malfunction rate amount 500 and $2180 \cdot 10^{-6}$. The majority of values fluctuates between 900 and $1800 \cdot 10^{-6}$.

The course of the technical reliability and operational reliability of the computer-amplifier of the PB-20 D is shown by Figure 27.

/85

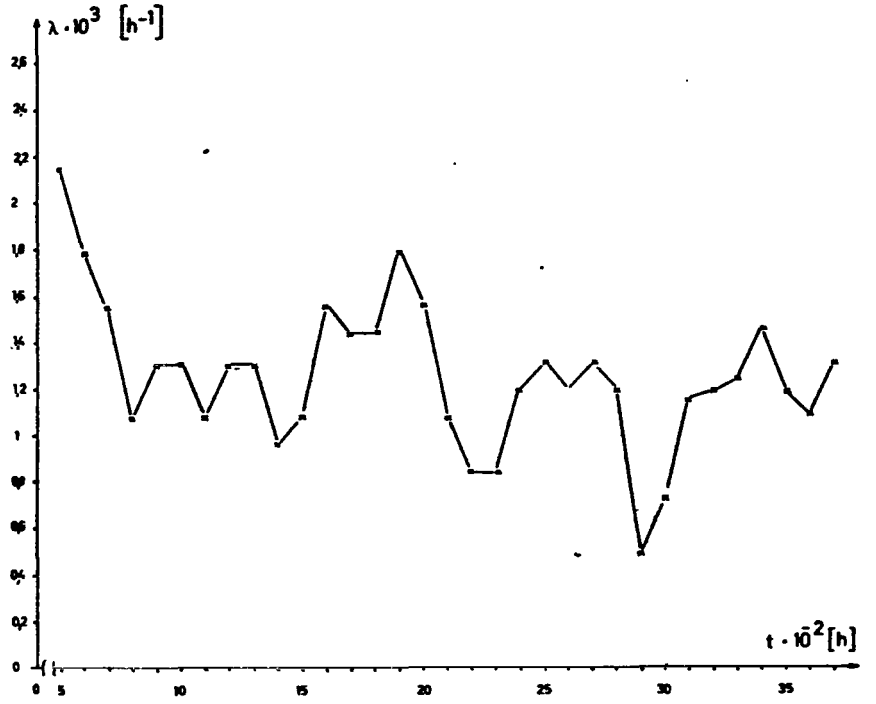
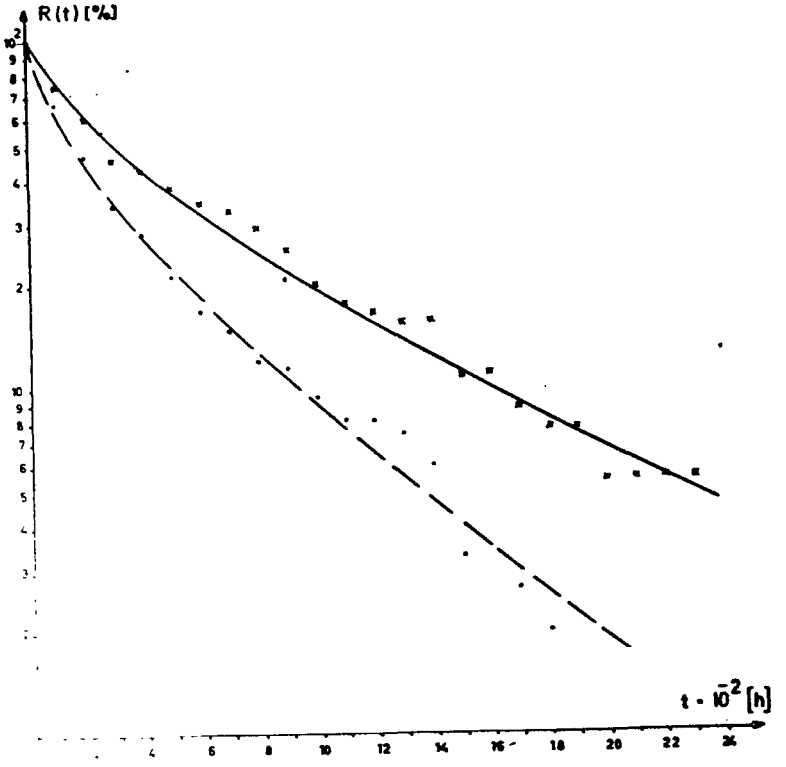


Fig. 26. Malfunction Rate of the Computer-Amplifier of the PB-20 D

/86



----Operational Reliability

———Technical Reliability

Fig. 27. Reliability of the Computer-Amplifier of PB-20 D.

Computer-Amplifier of the SP-50 (Sperry)

The malfunction rate of electronic assemblies is strongly temperature-dependent. A corresponding investigation [87] on the assemblies of roll, pitch and yaw electronics is shown by the results presented in Figure 28. It can be seen that the malfunction rates /87 rise stronly from ca. 40° C and have reached twice the value at 70° C as at 20° C.

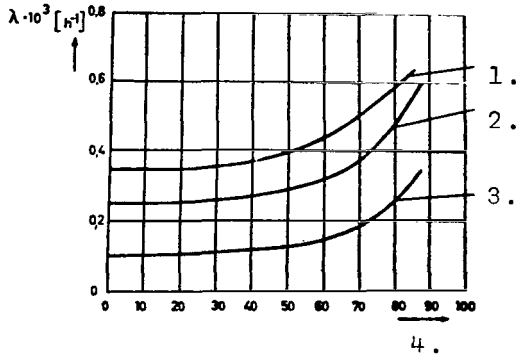


Fig. 28. Malfunction Rates of the Computer-Amplifiers of the SP-50.

1. Roll Electronics
2. Pitch Electronics
3. Yaw Electronics
4. Temperature (°C)

The malfunction rates amount here at a plausible operational value of 40° C:

Roll electronics:	$360 \cdot 10^{-6}$
Pitch electronics:	$270 \cdot 10^{-6}$
Yaw electronics:	$100 \cdot 10^{-6}$

As opposed to that, the values, as they were able to be obtained from the publications of United Air Lines, amount to:

Roll electronics:	$503 \cdot 10^{-6}$
Pitch electronics:	$663 \cdot 10^{-6}$
(resp.	$590 \cdot 10^{-6}$)
Yaw electronics (doubled)	$508 \cdot 10^{-6}$
Yaw electronics (1 unit)	$254 \cdot 10^{-6}$

The occurring differences lie within possible statistical /88 fluctuations. The values of Sperry were, moreover, ascertained in a bench test, so that, eg., an environmental loading by means of vibration is not present.

Summary of the Malfunction Rates of Various Computer-Amplifiers

The results of the evaluations of the publications of the various commercial airlines for computer-amplifiers of flight systems of the third generation are compiled in Table 39.

The removal rates E as a function of time of computer-amplifiers of various autopilots are reconstructed in Figure 29.

These results fater Table 39 as a mean value of the malfunction rates of the computer-amplifier a value of

$$\lambda = 1{,}250 \cdot 10^{-6}$$

TABLE 39. REMOVAL RATES OF COMPUTER-AMPLIFIERS OF VARIOUS AUTOPILOTS

Assembly	Manufacturer	Autopilot	Aircraft	Source	Year	Malfunction Rate $10^6[h^{-1}]$
Amplifier	Bendix	PB-10A	V-814 L-1049G	DLH	1961	1,196
Computer 15453	Bendix	PB-20 D	B-707	AF	1965	1,480
Computer 15453	Bendix	PB-20 D	B-720	UAL	1965	1,610
Amplifier	Smiths	SEP-4	Viscount V-814	BEA	1962	450
Amplifier	Smiths	SEP-4	Comet	BEA	1962	490
Computer-flight Control Stabilization	Sperry	SP-30	DC-8	UAL	1965	1,480 (860) (620)
Amplifier-Main A/P	Lear	L-102 B	Caravelle	UAL	1965	2,050
Roll-Control	Sperry	SP-50	B-727	UAL	1965	(503)
Pitch-Control						(663)
2 Yaw-Control						(508)
Total Control						1,674
Roll-Control	Sperry	SP-50	B-727	Sperry	1962	(360)
Pitch-Control						(270)
2 Yaw-Control						(200)
Gesamt						830

+ Values in parentheses refer to subassemblies.

AF = Air France

DLH = Lufthansa

BEA = British European Airways

UAL = United Air Lines

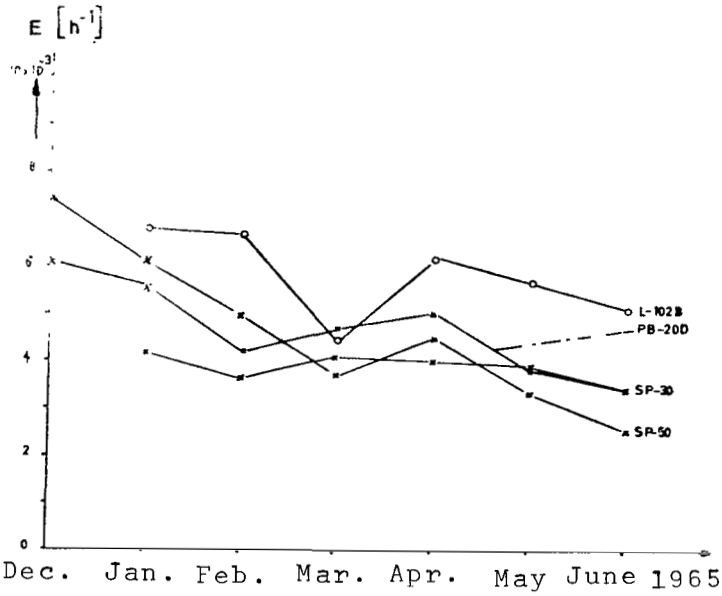


Fig. 29. Removal Rates of Computer-Amplifiers

2.3.1.3. Servomotors

2.3.1.3.1. Electrical Servos

If electrical servos serve the purpose of adjusting the aero- /90
dynamically effective surfaces for the control of the aircraft, they consist of the actual electrical motor with an attached generator for the preduction of a velocity signal, a position feedback, a reduction gear, a magnetic clutch and an over-travel clutch.

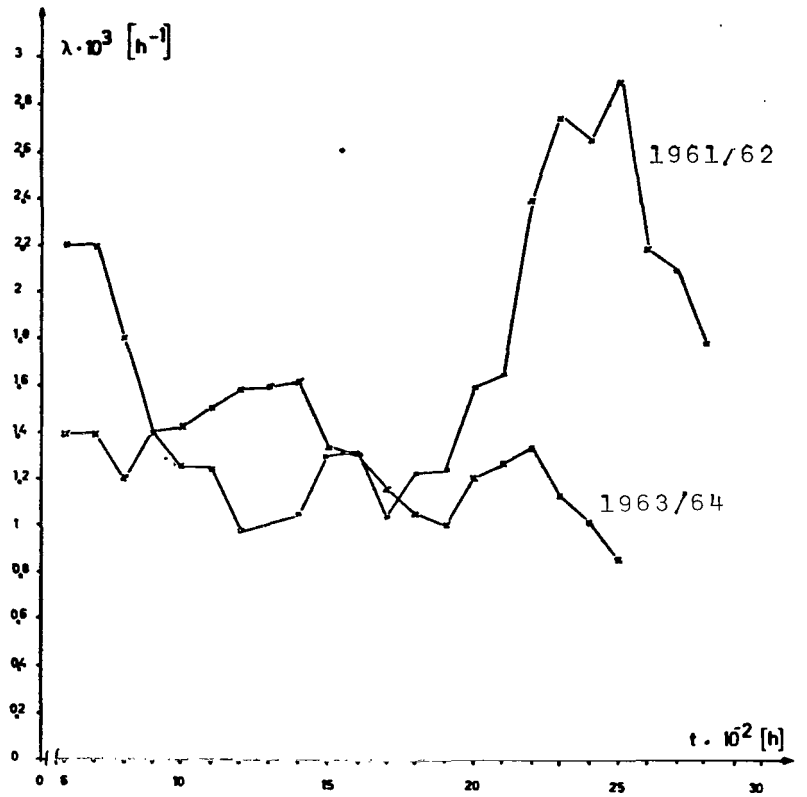
Servomotors of the Autopilot PB-20 D

The following malfunctions on the servos on the PB-20 D of the Boeing 707 fleet (24 aircraft) ascertained in flight operation were able to be obtained from publications of Air France.

TABLE 40. MEAN VALUES OF MALFUNCTION RATES AND MTBF OF ELECTRICAL ACTUATORS OF THE PB-20 D

Assembly	No. of Actual Defects	No. of Flight Hours	Malfunction Rates	MTBF
Vane Servo (1964)	29	152,800	$189 \cdot 10^{-6}$	5,270
Servo Trimm (1961/62)	54	29,245	$1,840 \cdot 10^{-6}$	541
Servo Trimm (1964)	71	60,225	$1,180 \cdot 10^{-6}$	848

The more exact temporal dependence and static fluctuations of the malfunction rates of the servo trimms are presented in Figure 30.



/91

Fig. 30. Malfunction Rates of Servo-Trimms of the PB-20 D

Figure 31 shows the course of the operational reliability of the servo trimms for the time span 1961/62 and 1963/64. /92

There results from the statistics of United Air Lines for the vane servo of the PB-20 D a removal rate of $103 \cdot 10^{-6}$ and for the servo trimm a removal rate of $840 \cdot 10^{-6}$. Further values of servo-motors of the various autopilots are reconstructed in Table 41.

If one neglects the malfunction rate of the apparently very unreliable servo trimm of the PB-20 D, a mean value of the malfunction rates results from Table 41 at

$$\lambda = 64 \cdot 10^{-6}$$

TABLE 41. REMOVAL AND MALFUNCTION RATES OF VARIOUS ELECTRICAL ACTUATORS.

Assembly	Autopilot Commerical Line Aircraft	No. of Removals	No. of Actual Defects	Total No. Flight Hours	Removal Rate·10^6	Malfunction Rate·10^6
Vane Servo	PB-20 D	--	29	152,800	--	189
Servo Trimm	AF	--	71	60,225	--	1,180
	B-707					
Vane Servo	PB-20 D	8	--	73,719	103	51
Servo Trimm	UAL	62	--	73,719	840	420
	B-720					
Elevator Servo	SEP-4	--	--	83,800	--	50
Aileron Servo	BEA	--	--	83,800	--	30
Torqueli-miter	V-814 (Viscount)	--	--	83,800	--	30
Elevator Servo	SEP-4, BEA	--	--	34,141	--	80
E. Trimm Servo	Comet	--	--	34,141	--	90
	SP-30					
Servo+)	UAL	14		67,178	176	88
	DC-8					
Servo(Auto-pilot)	SP-30	5		62,945	79	40
	UAL					
Servo(Rot.-Act.)	B-727	9		62,945	143	71
Servo+)	L-102B, UAL	2		22,090	75	37
Servo Trimm	SE-210	1.3		22,090	60	30

+ Mean value from, in each case, 3 units.

/93

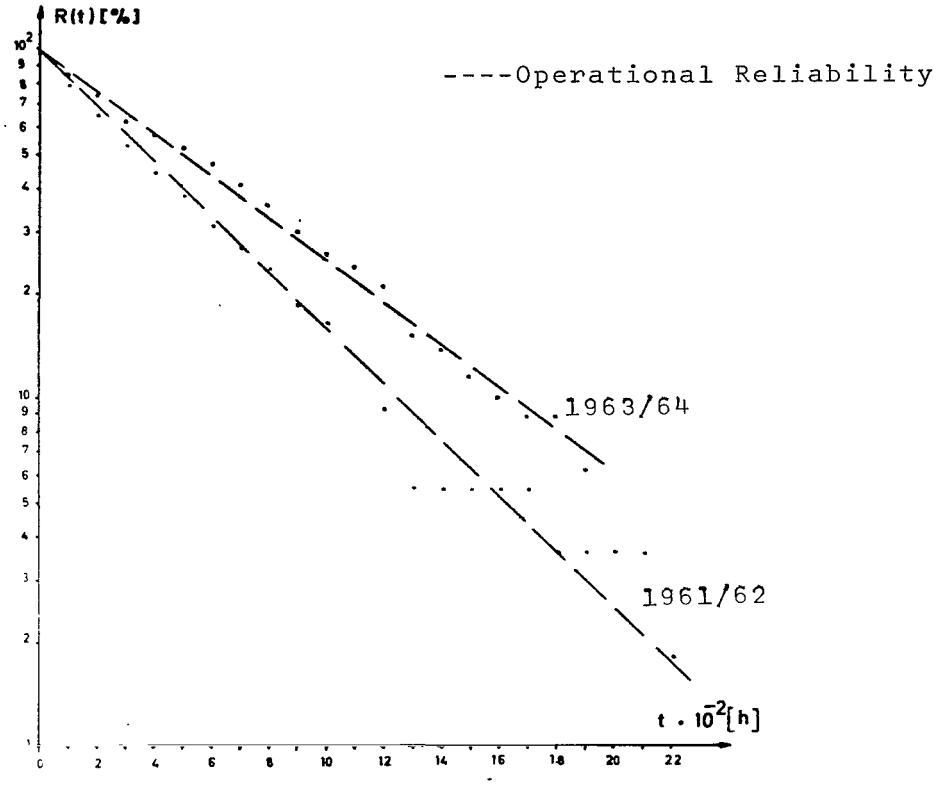


Fig. 31. Reliability of Servo Trimms of the PB-20 D

2.3.1.3.2. Hydraulic Servomotors

In the case of high performance aircraft the rudder adjustment /94 frequently does not take place through electromechanical servomotors, rather through electrohydraulic servomotors.

The electrical adjustment signal of the computer-amplifier is conducted to the booster of the servomotor over an electrohydraulic servo value. The mechanical activiation by the pilot controls the same servomotor over a mechanical adjustment of the booster.

The reliability of the hydraulic feed will be left out of consideration here; great progress has been made in the area of the reliability of the hydraulic aircraft system; more detail on this matter can be obtained in [99-102] as well as [114, 124, 125].

Only a few data were available to the author on the reliability of hydraulic servos.

Elliot Bros.[8] Ltd. indicates the following values for malfunc-

[8] Accommodatingly provided at the request of the author (Feb. 1966).

tion rates.

Torque pick-up motor	=	$10 \cdot 10^{-6}$
Servo value	=	40
Booster	=	16
Total	λ =	$66 \cdot 10^{-6}$

Smiths Av. Div.[9] indicates for the entire servomotor a value of /95

$$\lambda = 100 \cdot 10^{-6}$$

Earles and Eddins [89, 90] give the following data for hydraulic boosters:

Lower boundary value	=	$0.86 \cdot 10^{-6}$
Mean value	=	$12.5 \cdot 10^{-6}$
Upper boundary value	=	$36.6 \cdot 10^{-6}$

According to Earles and Eddins, the malfunction rate for servo values is:

Lower boundary value	=	$16.8 \cdot 10^{-6}$
Mean value	=	$30.0 \cdot 10^{-6}$
Upper boundary value	=	$56.0 \cdot 10^{-6}$

There resulted for a complete servomotor in first approximation (sum of servo value + booster) the following malfunction rates:

Lower boundary value	=	$17.6 \cdot 10^{-6}$
Mean value	=	$42.5 \cdot 10^{-6}$
Upper boundary value	=	$92.6 \cdot 10^{-6}$

The values of Elliot, Smith and Earles and Eddins agree well. If one forms the mean value of these indicated malfunction rates, one could assume as a typical malfunction rate of an electrohydraulic servomotor

$$\lambda = 69 \cdot 10^{-6}$$

2.3.1.4. Other Assemblies

Aside from the assemblies discussed to this point, there are additional components that belong to the two flight control systems. /96

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[9] Accommodatingly provided at the request of the author (Feb. 1966).

TABLE 42. REMOVAL AND MALFUNCTION RATES OF OTHER ASSEMBLIES

Assembly	Autopilot Commercial Airlines Aircraft	No. of Premature Removals	No. of Actually Determined Defects	Total No. Flight Hours	Removal Rate $E \cdot 10^6$ h^{-1}	Malfunction Rate $\cdot 10^6$ h^{-1}
Control Unit	SEP-4, BEA Viscount	--	--	83,880	--	330
	SEP-4, BEA Comet	--	--	34.141	--	460
	SP-30, UAL DC-8	68		76,178	893	
	PB-20, UAL B-720	38		73,719	515	
	SP-50, UAL B-727	51		62,945	810	
	L-102B, UAL Caravelle	8		22,090	362	
Control Unit - Dual Controller	VC-10, BOAC VC-10	38	32	37,857	1,004	851
Position Indication	SP-30, UAL DC-8	4		76,178	53	
	PB-20, UAL B-720	1		73,719	13	
	SP-50, UAL B-720	12		62,945	190	
Position Indicator	SP-50, UAL B-727	14		62,945	222 (6)	
	PB-20, UAL B-720	15		73,719	202 (3)	

It is essentially a matter of the following assemblies:

Control unit (controller, flight panel)

Trimm indicator

Position transmitter

However, in each case according to autopilots type, still further assemblies can be components of the system (e.g., current distributor boxes, etc.).

Removal and malfunction rates of the above cited assemblies have been compiled in Table 42.

2.3.1.5. Summary

The typical values of the malfunction rates of assemblies of modern autopilots (third and fourth generations) are reconstructed in Table 43, as they were obtained in the preceding sections. /98

A rounded off mean value should be understood as a typical value.

The malfunction probabilities of autopilot models will be able to be estimated with the help of the typical malfunction rates further below (point 8).

TABLE 43. TYPICAL MALFUNCTION RATES OF AUTOPILOT ASSEMBLIES

Assembly	Malfunction Rate $\lambda \cdot 10^6$ h^{-1}
Position Gyro	500
Stabilized Platform	1,500
Rate Gyro	70
Accelerometer	50
Compass Directional Gyroscope System	800
VHF-Nav. Receiver (VOR, ILS)	1,000
VHF Glide Path Receiver	500
NDB Receiver (ADF)	800
Combined Altitude and Pressure Head Sensor (Pilot-Static)	500
Computer-Amplifier (for all 3 axes)	1,250
Electrical Servomotor	65
Electrohydraulic Servomotor	70
Control Unit	350

2.3.2. CONSTRUCTIONAL COMPONENTS

2.3.2.1. General Information

The constructional units which find application in the manu- /99
facture of light control systems are equal in their functions of light control systems are equal in their functions to those which are employed in other areas of technology. However, special demands are made of them, which result from altered environmental conditions and the loads associated with them. These are, especially, vibration, shock, temperature, and moisture, which show an altered spectrum (Fig.. 9, 10, 11, 12).

The differing spectra of vibration, shock, temperature moisture are compiled in Figures 9, 10, 11, 12 after Earles and Eddins (AVCO) [89, 90], as they are typical for individual locations of installation such as orbits of a satellite, laboratory structure, earthbound, fixed installations, ships, ground vehicles, railroads, aircraft, early and present used missiles.

A considerable amount of literature is present on these reliability and malfunction rates of constructional units [83], since it has become customary to demand from the manufacturers of the constructional components, besides function parameters, also data on malfunction rates.

2.3.2.2. Malfunction Rates

A comparison of the distribution of all malfunction rates on various places of installation is reconstructed in Figure 32 and after [89, 90].

Malfunction rates of constructional units are compiled in /100
Table 44, which were taken from the most complete publications available to date.

They are the following:

1. Earles, D.R. and M.F. Eddins (AVCO Corporation): Failure Rates [89, 90].
2. Military Standaradization Handbook (MIL-HDBK 217): [88] Reliability Stress and Failure Rate Data for Electronic Equipment/
3. RADC Reliability Notebook (PB 161 894 [parts 1, 2, 3]) of the U.S. Department of Commerce, National Bureau of Standards, [103].
4. Honeywell: M.H. Aero-Report 2685-Tr 1 [92].

The values of 2 (MIL-Handbood 217) agree to a large extent with the values of 3 (RADC-Notebook), since the MIL-Handbook represents /101
a continuation of the Rome Air Development is indicated in Table 44 as a source.

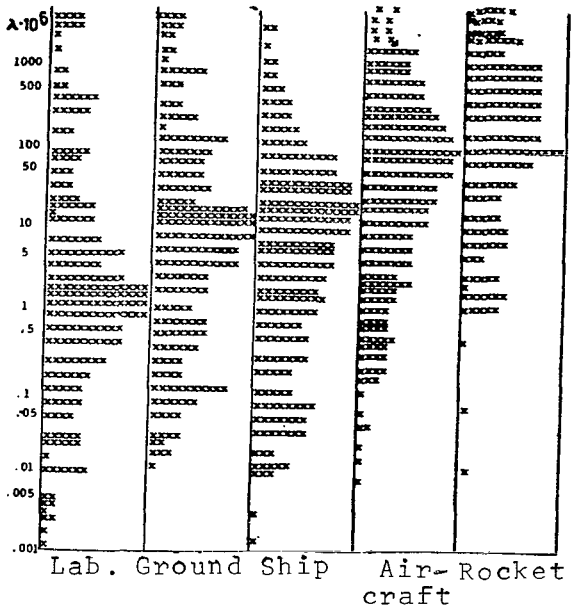

Fig. 32. Distribution of Malfunction Rates of Constructional Units at Various Places of Installation (after [89, 90]).

Further values are taken from the Aero-report of Honeywell.

Malfunction rates are noted in the column "typical values", which became known to the author from various other sources in comparison with 1, 2, 3 and 4.

2.3.2.3. Distribution of Malfunction in Flight Control Systems Over the Individual Constructional Units

Lufthansa determined the distribution of malfunction over the individual constructional components reconstructed in Table 45 in the time span from March 2, 1960 to December 31, 1962, with, all told, 63,000 flight hours [104].

2.3.2.4. Special Problems in the Consideration of Malfunction

2.3.2.4.1. Electrical and Electronic Constructional Units

Electrical constructional units can be drawn together into groups which are subject to approximately the same malfunction mechanisms:

1. Semiconductor components (transistor, diodes)
2. Resistances, potentiometers
3. Condensors
4. Inductivities, (Choking Coils, Transformers, Windings of Motors, Generators, Syncros)
5. Switches, relays
6. Plugs, Soldered spots, Connections
7. Integrated Circuits

Amplifier tubes (vacuum tubes) no longer play a role in avionics. Also, constructional units of heavy current engineering find, in practice, little application in flight control.

It has been shown that the malfunctions of electrical components are temperature-dependent.

TABLE 44. MALFUNCTION RATES OF CONSTRUCTIONAL UNITS

Constructional	AVCO (Earls & Eddins)	Honeywell	MIL-Hdbk 217	Typical Values
Condensor		0.4	0.11	
" , Paper	0.05	0.8	0.24	
" , Tantalic Capacitor	0.6	0.9	0.58	
" , Oil Electrolyte	0.3			
" , Metallic Paper		0.8		
" , Ceramic, Mica	0.0625	0.8	0.05	
" , Paper under 600 V	0.025			
" , Paper over 600 V	0.09			
" , Quality Ceramics	0.06			
Adjustable Disc Condensor	0.1625			
" , Air	0.034		0.1	
" , Ceramic	0.155		0.31	
Condensor, General	0.1	0.74	0.23	1.0
Resistance, Layer	0.045	0.5	0.65	
" , Mass	0.043		0.11	
" , Wire	0.087	0.7	0.68	
" , Fixed	0.03			
" , Precision	1.67		0.79	
Resistance, General	0.159	0.6	0.56	0.5
Potentiometer, Layer	0.25			
" , Mass	0.1			
" , Wire	1.4	5.0		
" , Motor Driven	5.485			

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Constructional	AVCO (Earls & Eddins)	Honeywell	MIL-Hdbk 217	Typical Values
Potentiometer, Layer (Con't)				
" , Thermal				
" , Heat				
Potentiometer, General	3.0	5.0		3.0
Transistor, for Amplifiers	0.5			
" , Germanium	0.3			
" , 2 m W	0.4			
" , 20 m W	0.7			
" , 200 m W	1.91			
" , Mesa	0.07			
" , Silicon	0.5	11.8		
" , for electronic switches	0.4			
" , Boundary layer	0.12			
" , Silicon digital				
" , Silicon analogous				
" , power				
Transistor, General	0.61	11.8		5.0
Thermistor	0.6	0.7		0.65
Diode, Germanium	0.157			
" , Power	0.42			
" , Selinium	0.2			
" , Silicon, rectifier	0.2	1.0		
" , Silicon, carbide	0.10			
" , Breakdown(Z-)	0.15			

Constructional	AVCO (Earls & Eddins)	Honeywell	MIL-Hdbk 217	Typical Values
Diode, Germanium (Con't)				
" , Shockley				
" , four layer				6.0
Diode, General	0.2	1.0		1.0
Toroidal, reactor (for magnetic amplifier)		4.5		
Pressure-transformer				
Gyro, rate	7.5			150
" , vertical	10.0	100-300		500
Gyro, General	15.0	200		
Motor, A.C.	5.24			
" , D.C.	9.36			
" , hydraulic	4.3			
" , induction	8.6			
" , servo	1.51			
" , synchron	0.359			
Motor, electric, general	0.3			10.0
Motor, general	4.5			4.5
Generator, A.C.	15.0			15.0
" , N-F (Audible range)	0.35			
" , D.C.	12.4			
Generator, general	0.9			0.9
Lamp, general	0.625			5.3
Switch, magnetic (solenoid)				
" , Tipping-pressure				

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Construction	AVCO (Earls & Eddins)	Honeywell	MIL-Hdbk 217	Typical Values
Switch, magnetic (solenoid) (Con't)				
" , rotation				
" , micro	0.25+			
" , servo				
Switch, general/per contact	0.25			5.0
Plug connections				
Per plug of connection	0.003-2.0	0.14		0.1
Relay, armature	0.3+			
" , signal	0.26+			
" , power	0.3+			
Relay, sensitive				
" , thermal	0.4+			
" , miniature	0.06+			
Relay, general	0.25+	15.5		15
Vibrator	0.5			
Accelerometer (linear)	2.8-8.0	0.1-1.6		
Delay line	0.11			
" , system				
Spring, restoring force	0.012			
" , for adjustment	0.22			
Spring, general	0.105			0.1
Directional Coupler	1.52			
Vibrator	0.5			
Fuses, Hydraulic	1.61			
" , pneumatic	2.5			

/104

Constructional	AVCO (Earls & Eddins)	Honeywell	MIL-Hdbk	Typical Values
Fuses, general	0.5			2.75
Thermostat	0.3			
Ammeter	0.29			
Coupling, Slip	0.3			
" , magnetic	0.6			
" , claw or tooth	0.063			
Clutch, general	0.06			3.0
Amplifier, magnetic	0.085+			5.0
" , signal (low power)	3.11			
" , control	5.33			
Amplifier, general	0.29			2.0
Resolver				20.0
Booster servo	12.5			
Final control element, support servo	12.5			
Final control element, general	5.10			10.0
Connection mechanism and joint	10.97			10.0 /105
Piston, hydraulic	0.2			
Pick-off, A.C.				4.0
Torque Motor				10.0
Transductors				5.0
Contact strip				
Servo value, electro-hydraulic servomotor	30.0			30.0
Transmission	0.63			0.6

Constructional	AVCO (Earls & Eddins)	Honeywell	MIL-Hdbk 217	Typical Values /106
Differential linkage	1.0			1.0
Solder spot/lines				0.01
Transformer, power	0.5	17.0		
" , synchro	0.028			
" , signal		4.0		
" , differential		21.0		
Transformer, general	0.15	14.0		5.0
Screen-net-NF- reactor				
Inductivity, tunable (mech.)	0.008			
Inductivity, with Pick-off				
Inductivity, general	0.02			1.0

+ are indicated in $F/10^6$ connections

It is assumed [88] that the malfunction rate of semiconductor components like transistors and doides are, in first approximation, a function of the boundary layer temperature T. /107

$$\lambda = f(T)$$

This temperature results from the environmental temperature T_A and the temperature increase produced in the semiconductor by absorbed power. The following relation is indicated in [88] for the temperature T at the collector:

$$T = T_A + \Theta P_K \qquad (9)$$

Here: /108

T_A = Environmental Temperature (°C)

Θ = Thermal Resistance (°C/mW)

P_K = Mean Converted Power (mW)

TABLE 45. DISTRIBUTION OF MALFUNCTIONS OF AUTOPILOTS OVER THE INDIVIDUAL CONSTRUCTIONAL UNITS AFTER [104]

No.	Constructional Unit and Other Sources of Defects	Portion of the Total Number of Malfunctions (%)
1.	Semiconductors (diodes, transistors)	3.7
2.	Electrical Constructional Units (Resistance, Condensors, Potentiometers)	7.4
3.	Relay	16.8
4.	Wiring (Insulation, Interruptions, Short Circuit)	4.0
5.	Mechanical Parts Exposed to Wear (Bearings, Rotors, Damping Piston, Couplings, Transmission, Shock Absorbers)	42.6
6.	Contacts (Switches,	5.7
7.	Fuses	4.0
8.	Untight (Air data computer)	0.3
9.	Out of Tolerance (Calibration necessary, coupling adjustment, synchro-zero adjustment)	15.5
		100.0

A typical value in the case of good heat lead off (large surface cooling surface contact) is indicated at $\Theta = 0.11$, with heat lead-off only by convection (as e.g., in transistors) $\Theta = 0.25$.

Experimental determination of the malfunction rate of semiconductor components has resulted in the fact that the malfunction rate λ as a function of the environmental temperature T show, to begin with, a flat, horizontally running part and, from a certain temperature on, a strongly ascending course. The temperature at which the sharp bend occurs is all the lower the smaller the converted power.

Through the standardization of the temperature axis, Figure 33 holds true both for germanium transistors and silicon transistors. The standardization is undertaken in the following way: /109

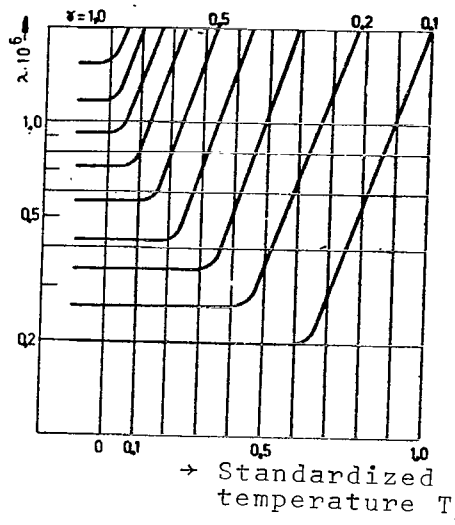

Fig. 33. Malfunction Rate of Transistors as a Function of Standarized Environmental Temperature after [88], p. 49.

$$T_N = \frac{T_A - T_{min}}{T_{max} - T_{min}} \qquad (10)$$

where

T_A = Environmental temperature

T_{min} = Lower boundary temperature

T_{max} = Maximally permissible temperature

Chosen as a parameter is the loading ratio

$$\lambda = \frac{\text{actual loading [mW]}}{\text{nominal load}} \qquad (11)$$

The curve groups of the malfunction rate for semiconductor diodes show lower values. Only a boundary layer and two contacts are present in diodes; the number of possible sources of defects is, all told, slighter than in the case of transistors.

The curve groups presented in Figure 32 also resulted after [105] when the physical-chemical model of the Arrhenius formula was used as a basis.

2.3.2.4.2. Mechanical Constructional Units

The reliability of mechanical constructional units is, in first analysis, a problem of choice of materials (Rossow [73]). Strength fatigue strength, creep strength depending on time, among other characteristic magnitudes of the material form the bases of the realization of technical ideas in light construction engineering in aeronautics.

Frequently, the principle of redundant placing of the structures is found in precision engineering and in the construction of aircraft.

3. DEVELOPMENTAL TRENDS OF MALFUNCTIONS RATES

3.1. Gyros

Developments appear in gyro engineering which effect, especial- /110
ly the bearings subject to friction, an improvement and reliability is expected from gas mounted gyros. Further advanced designs predict magnetic supports produced by super conductivity or electrically mounted gyros.

Gas supported gyros are available as hydrodynamically or hydrostatically gas mounted realizations.

Optical gyros (lasers) are in the phases of development.

Malfunction rates of gas mounted gyros are difficult to obtain since such gyros are not yet employed in commerical aviation. However, hydrostatically as well as hydrodynamically gas mounted gyros are in use in the military domain as well as in space travel.

The firm Nortronics indicated in [95] two various malfunction rates for stabilized platforms after comprehensive findings with gas supported gyros. The smaller malfunction rate holds true for a platform with gas mounted gyros, (Integrating rate gyros), the larger one for the platform with ball bearing gyros (compare 2.3.1.1.1.2.).

$$\lambda = 417 \cdot 10^{-6}$$
$$\lambda = 762 \cdot 10^{-6}$$

It is known that the predominant part of the malfunction of ball bearing gyros can be tracked back to the support of rotor and frame, so it appears justified to assume a lower malfunction rate for free gas mounted gyros as well.

It seems possible that a malfunction rate (with rationally /111
dimensioned maintenance intervals) of

$$\lambda = 100 \cdot 10^{-6}\ h^{-1}$$

is attainable.

3.2. Computer-Amplifiers

The greatest improvement of autopilot constructional units might be expected of the computer-amplifiers. This would also be of urgent import from the standpoint of systems reliability, since

these constructional components have the greatest share of the total system malfunction probability (compare Table 43).

The assumption of an expected reduction of the malfunction rates of computer-amplifiers appears justified for the following reasons:

1. Decreasing malfunction rates of conventional electronic constructional units.

2. Extensive replacements of circuits of individual constructional components by integrated circuits.

3. Internal redundancies in the instruments.

On 1 and 2, compare further below (3.4).

3. Internal redundancy does, to be sure, find application in a smaller range, i.e. in individual critical constructional units in the computer-amplifiers considered to this point. However, only in the most recent development has use been made to a greater extent of internal redundancy. This was made possible especially by the decrease of mass and volume of the constructional units associated with the increasing micro-miniaturization of electronics ([106] to [110]).

Reliability Increase by Means of Digital Control Engineering /112

The processing of the signals of the sensors of the flight control system likewise takes place in the conventional manner in an analog form in the computer-amplifiers. Here, AC and DC current engineering is applied.

General Electric [113], Hawkwer-Siddeley-Dynamics [111] and Elliot [112] propose for the improvement of reliability of the computer-amplifiers impulse length-modulation for data processing.

There can be cited as an advantage of such control engineering:

The reliability of semiconductors, especially of transistors, is larger in an application as switches than in the case of application of analog amplifiers.

Such circuits can be obtained as integrated circuits in micro-miniaturized realization and can be redundantly installed as a consequence of very small dimensions.

On the whole, it seems possible to lower the malfunction rates of computer-amplifiers for flight control systems by the factor 5 to 10.

3.3. Servomotors

Development in the case of servomotors for aircraft controls shows tendencies toward electrohydraulic servomotors, since the forces necessary for control surface adjustment are becoming continuously larger. These are multiply constructed for reasons of reliability and fed by several independent hydraulic systems (to date, two supply systems). The power-rate ratio is more favorable in the case of hydraulic servomotors than for electrical ones; however, an electrical supply system can also offer advantages in the case of long supply lines under certain circumstances. From /113
the standpoint of redundancy and control engineering, the power-coupling of regulated quantities in hydraulic multiplex servomotors has considerable advantages. In this area, a central point of developmental activity is formed, which was initiated by the firms Hobson, Dowty, Sperry and Hydraulic Research [124, 125].

Improvements of the present malfunction rates of hydraulic servomotors can also be expected from investigations in the area of hydraulic fluid, as for example, on the problem of cavitation erosion [114].

3.4. Constructional Units

Great efforts have been taken to improve the reliability of constructional components both with respect to materials and manufacturing. The following can be cited as an example for the developmental trend of malfunction rates of constructional components:

Through special reliability programs in the USA, standards have been established for lower malfunction rates of electronic constructional components for the Polaris, Minuteman Programs, as well as for the space programs such as Mercury, Gemini, Apollo. In the preparation of instruments for these programs, only constructional components may be employed which fulfill the set standards. The standards are presented in Figure 34 [115].

The precise, specified standards for the Minuteman program can, for example, be taken from the MIL-Handbook 217, [88], p. 169.

A new reliability program with further heighted demands, /114
especially for semiconductor constructional components are the JAN-TX-specifications of the aviation industry for the equipment of the aircraft F-111 [116].

Integrated circuits will have especial influence on the reliability of aviation and space electronics. These assumptions are supported on the following points:

1. The number of soldered spots in circuits is lowered by more than one order of magnitude.

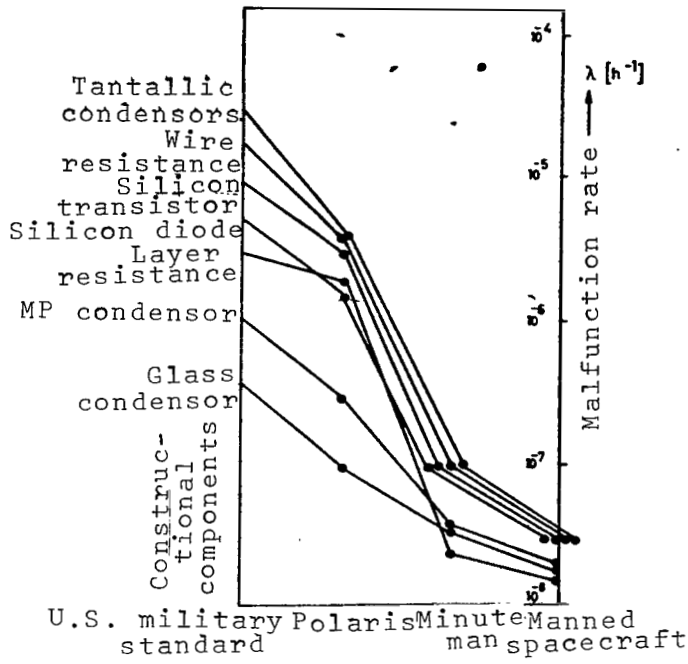

Fig. 34. Standards for Malfunction Rates for Various US Programs.

2. Thermal-mechanical influences, which can develop forces, do not come to expression as a consequence of the integrated positioning of the constructional components onto carriers of good heat conductivity. /115

3. The sealing of the integrated circuit prevents corrosion processes, even in the presence of an aggressive atmosphere.

4. Internal redundancies are possible to a larger extent through a decrease of mass and volume.

After Reference [117], the malfunction rates of integrated circuits lie at

$$\lambda = 0{,}05 \cdot 10^{-6}\ h^{-1}$$

4. CRITICAL OBSERVATION OF THE MALFUNCTION PROBABILITIES OF CURRENT FLIGHT CONTROL SYSTEMS AND RECENTLY PUBLISHED PROPOSALS

4.1. On The Calculation of Malfunction Probabilities[10] With No Malfunction Rates

The malfunction probability Q is defined as the probability complementary to the survival probability R (Reliability). There therefore holds true

$$R + Q = 1 \tag{12}$$

The following context results from the definition of the malfunction rate h(t) (compare section 2.1.2,1) and of the reliability:

$$R(t) = \exp\left[-\int_0^t h(t)\,dt\right] \tag{13}$$

If the malfunction rate can be regarded in first approximation as constant, i.e.

$$h(t) = \lambda = \text{const.}$$

there results for the reliability the known exponential relation

$$R = e^{-\lambda t} \tag{14}$$

there then holds true for the malfunction probability Q

$$Q = 1 - e^{-\lambda t} \tag{15}$$

The time constant T of the exponential function is the reciprocal value of the malfunction rate /116

$$T = \frac{1}{\lambda} \tag{16}$$

[10]Compare to this section the pertinent books and publications on the theory of probability, on the theory of technical reliability References [74-82], as well as the appendix of [45].

this is frequently designated as MTBF (Mean Time Between Failures).

The designation (MTBF is derived from the experimental determination of this magnitude, where it is obtained as the sum of operational times divided by the number of malfunctions.

$$T = \frac{\sum t_i}{N}$$

The functions R and Q can then be written in the following way

$$R = e^{-\frac{t}{T}} \qquad (17)$$

$$Q = 1 - e^{-\frac{t}{T}} \qquad (18)$$

The course of these functions is presented in Figure 35.

The survival probability amounts to in the interval t = T

$$R = e^{-1} = 0{,}37 = 37\ \%$$

The malfunction probability Q

$$Q = 0{,}63 = 63\ \%$$

Moreover, the following approximation holds true as a result of the known expansion in a series of the function e^{-x} for small x

$$R \approx 1 - \lambda t \qquad (19)$$

$$Q \approx \lambda t \qquad (20)$$

4.2. Malfunction Probabilities of Flight Control Systems

Two possibilities come into question for the calculation of the malfunction probabilities of autopilots:

1. If the malfunction rate of the system in question is known, then the calculation of the malfunction probability from it is possible.

2. If the malfunction rate of the system is not known, then an attempt can be made, based on typical values of the malfunction rates of assemblies as they have resulted from 2.3, to estimate the

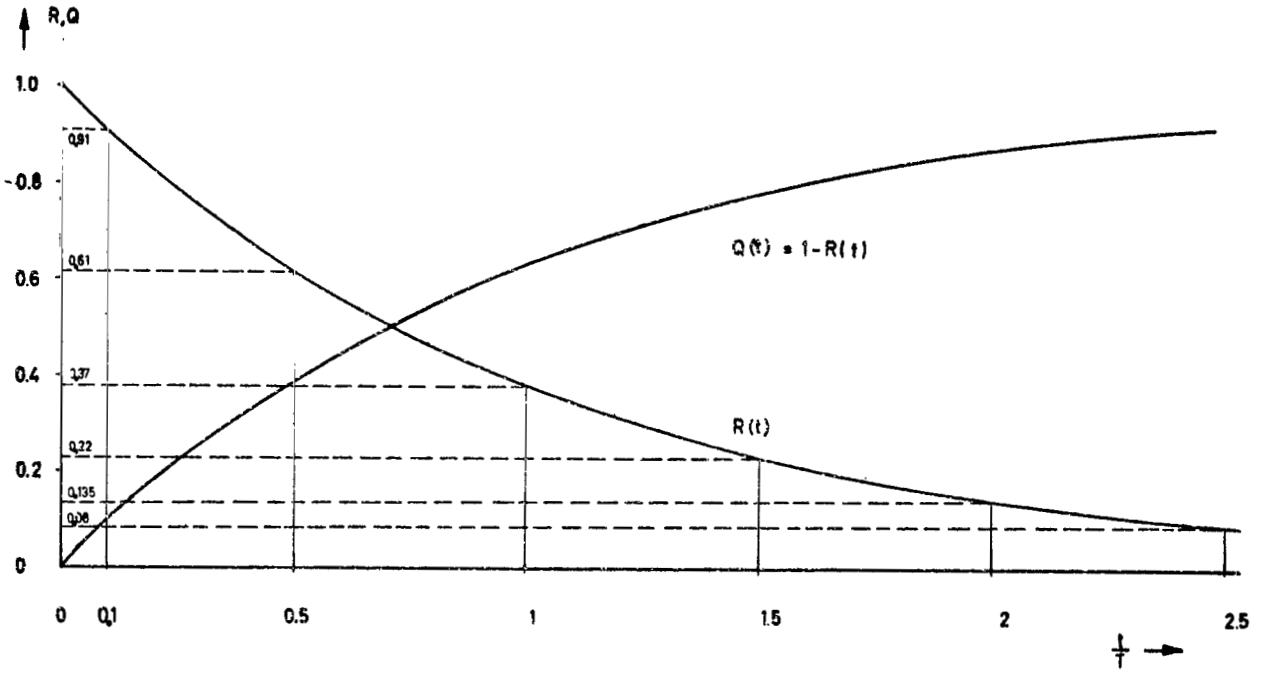

Fig. 35. Course of R(t) and Q(t) with Constant Malfunction Rate

malfunction probability of the system based on typical constructional designs. /118

The calculation is especially simple in the case of non-redundant systems as a result of the relation

$$Q = 1 - e^{-\lambda t}$$
$$Q \approx \lambda t \qquad (20)$$

The probability for the eventuality that a malfunction will occur during the operational time (of a flight) of one hour (t = 1) is then numerically equal to the malfunction rate λ.

With redundant systems, the calculation of the total malfunction probability must be undertaken from the malfunction probabilities of the assemblies which, for their part, can be determined from malfunction rates of assemblies (compare Section 5.2).

First Generation

Autopilot K 4u and K 12 (Siemens)

The estimation of the malfunction probability of these autopilots yielded for single axis (course control)

$$Q = 1{,}1 \cdot 10^{-3} \cdot t$$

Autopilot Lstz 14 (Askania - Werke) /119

The estimation of the malfunction probability of the course control allows to appear plausible a value of

$$Q = 2 \cdot 10^{-3} \cdot t$$

Autopilot A-2 (Sperry)

The estimation of the malfunction probabilities of the autopilot (3 Axes) based on the typical malfunction rates of autopilot assemblies resulted in a value of

$$Q = 2{,}5 \cdot 10^{-3} \cdot t$$

The malfunction probabilities of the autopilots of the first generation represent only crude approximations, since data from the flight operation of these autopilots were not available and, accordingly, malfunction rates had to be based on the present state of engineering. These values were investigated for the purpose of comparison with the malfunction probabilities of the present, much

more complex autopilots.

Second and Third Generations

It is a matter in all autopilots in the second and third generations of known redundant systems. The malfunction probabilities are, after (20), equal to the corresponding malfunction rates which are compiled in 2.2.2 for one hour of flight time.

Fourth Generation

Malfunction Probability of the VC-10 Autopilot (Elliot)

The system consists of two completely separate autopilots (Controller 1 and Controller 2), whose individual assemblies are monitored by control assemblies. If a difference between original assembly and control assembly appears, which is determined in the comparison monitor, controller 1 is shut down and this is indicated to the pilot by a warning light. The pilot can then switch on controller 2 with the control unit (dual controller). (Provision is made for automatic switching). The following assumption can be made as a malfunction criterion: /120

Systems malfunction appears if controller 1 and controller 2, or controller 1 and control unit (resp the automatic switching) become inoperative in the temporal interval under consideration. Probability for this amounts to

$$Q = q_1 q_2 + q_1 q_{ss}$$
$$= q^2 + q\, q_{ss}$$

Here, malfunction probability of one controller: $q_1 = q_2 = q$, q_{ss} = malfunction probability of control units.

Presupposed is that the pilot comprehends the warning of the monitor and switches in time, i.e. possesses a reliability of 1.00 himself. These probabilities for one hour come out to, with the malfunction rates of the system after Table 19

$$q = 3{,}091 \cdot 10^{-3}$$
$$q_{ss} = 0{,}85 \cdot 10^{-3}$$

The malfunction probability of the entire controller thus amounts to within one hour

$$\dot{Q} = (9{,}5 + 2{,}6) \cdot 10^{-6} = 12{,}1 \cdot 10^{-6}$$

Malfunction Probability of the Flight Control Systems SEP5 (Smiths) for the H.S. Trident and Short Belfast

Autopilot of the Trident

The autopilot in the aircraft H.S. Trident is currently installed in the so-called duplex version [118, 119]. A pre-stage of automatic landing, "Auto-Flare" can be carried out. The duplex execution of the flight control system consists of two completely independent controllers, consisting of sensors, amplifier-computers, and servomotors. The outputs of the two servomotors of any one control channel do however, function on one common, special output drive which is equipped with clutches in such a way that the entire autopilot is switched off and simultaneously a warning light is put into operation in the case of excess of a torque difference between the two control channels, as takes place in the malfunction of one channel. This special assembly is presented in Figure 36 /121 (after Reference [120]).

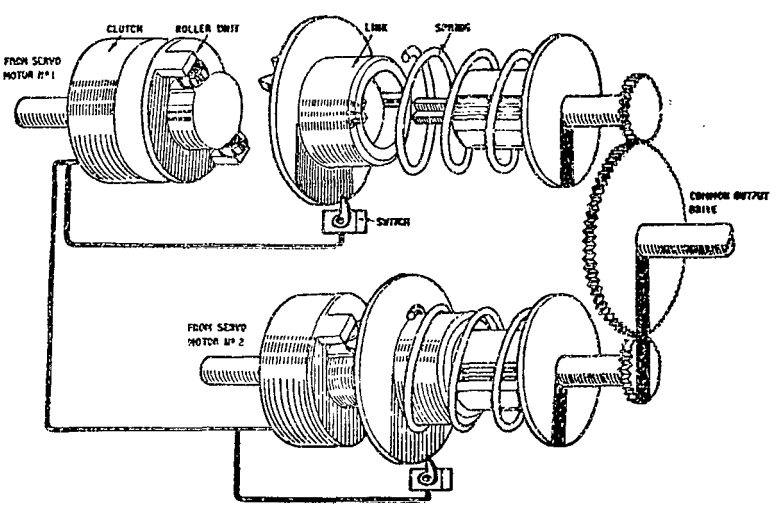

Fig. 36. Torque Comparison Unit of the Servomotors of a Duplex - Channel of the SEP-5 (Principal Sketch) from Reference [120].

From the standpoint of operational reliability, such an arrangement means, however, a deterioration as opposed to a simple flight control system, since a differentiation in terms of which of the two channels is defective is not possible. Also, the malfunction probability and malfunction rate of the system is increased by the factor two, since a systems malfunction occurs when one or the

other fails. There follows from that $Q_D = 2_q$, whereby Q_D = malfunction probability of the system (duplex), q = malfunction probability of the simple controller.

The reason for the choice of a duplex-systems configuration /122
of the SEP-5 lies in the increase of flight safety.

1. With the occurrence of a defect in one of the two channels, the malfunction of the entire system can be recognized and indicated to the pilot by the comparison unit, so that a manual control of the aircraft can be undertaken.

2. In this way, a malfunction of the system as a short circuit is avoided with certainty since the controller is automatically separated from the control surfaces by the clutches.

Autopilot SEP-5 as a Triplex-Version in the Short Belfast [121]

A power clutch from three independent control channels in a triplex electro hydraulic servo motor is undertaken in a triplex version of the SEP-5 (compare Section 6.1 [124, 125]). Malfunction of one of the three channels can be survived by the system (majority redundancy). The malfunction probability of the triplex system Q_T is smaller than that of the simple system $\underline{Q}$ (compare Section 5.5.3 [28]).

$$Q_T = 3q^2$$

From the standpoint of the freedom for repair, on the other hand, the probability is Q_R that the system will become in need of repair, i.e. that one of the three controllers will become defective. $Q_R = 3q$ is three times as large as in a simple system.

The conversion of the currently installed duplex system in the Trident into the triplex system is provided for at a later date in order to obtain the permission of the competent authorities for automatic landings ("Auto-Land") in scheduled line service.

Estimation of the Malfunction Probability of the SEP-5

Since malfunction rates of the SEP-5 were not available, the malfunction probability can only be estimated. If one assumes as the malfunction probability of the simpler controller per axis (Roll R Pitch Axis) a typical value of

$$q = 1{,}5 \cdot 10^{-3} = 1500 \cdot 10^{-6} \cdot t$$

for one hour, the malfunction probability of a triplex axis becomes /123

(majority redundancy presupposed, compare Section 5.5.3)

$$q_T = 3q^2 = 6{,}75 \cdot 10^{-6} \cdot t^2$$

For the entire controller (Roll and Pitch Axis) with neglect of the yaw damper

$$Q_T = 13{,}5 \cdot 10^{-6} \cdot t^2$$

The malfunction probability of the duplex version of the SEP-5 would, however, be, as opposed to that

$$Q_D = 4q = 6 \cdot 10^{-3} = 6000 \cdot 10^{-6} \cdot t$$

Autopilot MH-123 (Honeywell) for the Jet VTOL-Aircraft VJ-101 (EWR)

Since a flight control by the pilot did not seem possible in the case of this jet VTOL-Aircraft in the vertical flight phase, the flight control system should show an especially high reliability.

Honeywell used in the hover autopilot MH-123 for the aircraft VJ 101 C 1 redundancy for roll and pitch axis. Both channels are doubled, the position reference is given by three vertical gyros.

According to data of the manufacturer, there results, based on a reliability analysis [92], a malfunction probability of the position gyro for the redundant roll-resp pitch axis for one hour

$$q = 361 \cdot 10^{-6}$$

For the non-redundant yaw axis the value amounts to

$$q = 345 \cdot 10^{-6}$$

For the entire flight control system, which contains, aside from the cited position control for pitch and roll axis for hover flight, damping controls for aerodynamic flight, a malfunction probability Q is yielded:

Pitch Axis (Position and Damping Control)	$q = 579 \cdot 10^{-6}$
Roll Axis (" " " ")	$q = 579$
Yaw Axis (Damping Control)	$q = 345$
Propulsion-Unit Control	$q = 399$
Total	$Q = 1902 \cdot 10^{-6}$

/124

Malfunction probabilities of proposals for triplex redundant hover

autopilots.

The malfunction probabilities of various proposals for redundant hover autopilots (Fluggerätewerk Bodensee, Hawker-Siddeley Dynamics, Elliot Bros., Smiths Av. Div.) were investigated by Rössger and this author [45].

There, the following malfunction probabilities were ascertained for one hour and one control axis

$$0{,}9 \cdot 10^{-6} < Q < 5{,}7 \cdot 10^{-6}$$

In a few proposals, in which the yaw control was not to be multiplied, these resulted in

$$298 \cdot 10^{-6} < Q < 955 \cdot 10^{-6}$$

If one presupposes redundancy for all three controlled axes, there resulted for systems malfunction probabilities of the order

$$2{,}7 \cdot 10^{-6} < Q < 17{,}1 \cdot 10^{-6}$$

It must be considered that with these relatively small values sensors for the steering control circuit resp. their probabilities were not considered since the proposals comprehended only pure stabilization controls.

Malfunction Probabilities of the Further Redundant Systems and Proposals

Duplex Systems

Duplex systems offer no advantages over a simple system from the standpoint of reliability because of the principal inability to distinguish which of the comparable components is defective. If a defect appears, only the entire flight control system can be switched off. Through this, advantages result from the standpoint of flight safety, that in this way the trim, stable flight condition remains preserved and blank signals cannot appear. /125

Comparison of the two signal chains can take place in various ways.

Smiths (SEP-5 Duplex-Version) uses a special mechanical assembly (Fig. 36). Sperry [38] uses the rotation of a differential lever for the activation of a clutch switch.

The malfunction probability of such systems has already been indicated in the calculation of the SEP-5. It amounts to

$$Q = 2q$$

i.e. is twice as large as the malfunction probability q of the simple system, since malfunction in one channel or the other channel reads to a malfunction of the system.

It must be noted that frequently quadruplex systems are characterized as duplex systems. (VC-10-Regulator (Elliot) is designated as "duplicated monitored"). The assemblies which permit a comparison of the control signals, are then not counted in this case.

Triplex Systems

The simplest possibility of surviving a malfunction is provided by a triplex redundant setup. Various constructional possibilities (compare 6.ff) exist for the technical realization, which, in general, demand special assemblies. These possibilities do, however, not distinguish themselves from the standpoint of reliability.

It is common to all triplex systems that, at best, a malfunction can be survived (principal of majority redundancy). The malfunction probability of such systems has already been considered in the case of SEP-5.

Quadruplex Systems

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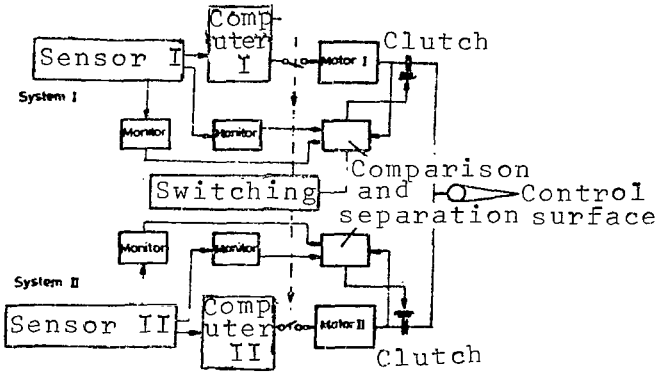

Fig. 37. Quadruplex Systems [35]

A quadruplex system is formed in such a way from, in each case, two pairs of sensors, computer-amplifiers that a malfunction in one pair effects a switching - over to the other doubled system. This principal finds application in a varied form in the proposals of the firm Elliot [35].

A malfunction probability of such a systems configuration can be estimated under neglect of the switching unit. For the double branch $q^+ = 2q$. For an axis $q_1 = (2q)^2 = 4q^2$. For the system (Roll and Pitch Axis) $Q = 2q_1$.

Example:

If one sets as a numerical value the malfunction probability /127 of a simple control channel with

$$q = 1{,}5 \cdot 10^{-3}.$$

the results for a quadruplex system

$$Q = 18 \cdot 10^{-6} \cdot t^2$$

Systems with Redundant Assemblies

Proposals have been made for constructing autopilots with triplex redundant assemblies. As an example, the proposal for an autopilot made by the Vereinigte Flugtechnische Werke, Bremen may be considered [25, 26].

In the proposed system, it is a matter of a position stabilization control for pitch and roll axis, in the case of which the sensors (vertical gyros) and the amplifiers are present in triplex within a controlled gyros) and the amplifiers are present in triplex within a controlled axis. This and a second intact channel are separated by a monitor and switching unit in the case of malfunction of a gyro or an amplifier. The second malfunction would lead to the malfunction of the entire control axis. A second malfunction can be survived by the introduction of a second switching logic which, to be sure, must be manually operated by the pilot. A more precise description of the system is given in [25] and [26]. In [26] an investigation of the reliability of the system has been performed. In the interests of a unified judgement, the there-found results can, however not be accepted since they were made, in part, after a lightly deviating basis of calculation, in part, on the assumption of a strongly deviating malfunction rate.

Figure 38 shows a simplified signal flux plan of an axis of the stabilization control.

The monitors are described in more detail in 7.3.

/128

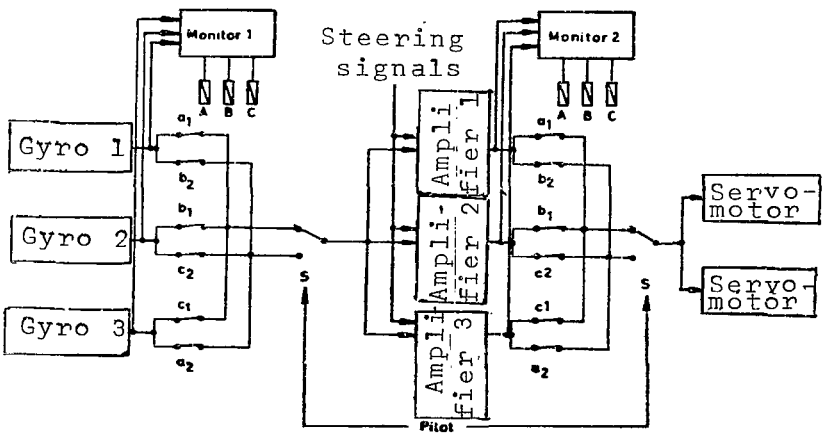

Fig. 38. Simplified Flux Plan of a Control Axis

The malfunction probability of an axis of such a control can be estimated. (The possibility of surviving a second malfunction is to be neglected since the pilot cannot intervene in the flight control with automatic flight piloting, resp. is not available for tasks of flight control.

Example:

If one assumes as numerical values the typical malfunction rates after Table 43 and for the malfunction probability of the monitors $q = 70 \cdot 10^{-6}$ after [45] for an hour and one axis,

$$Q = 6 \cdot 10^{-6}$$

However, it is a matter here only of the stabilization control without sensors for steering signals and of the malfunction probability of one axis. Accordingly, one obtains for a dual axis stabilization control /129

$$Q = 12 \cdot 10^{-6}$$

Bendix proposes in [39, 40] likewise a system with triplex redundant assemblies. The redundancy is realized there by so called "Voters" which are discussed in more detail in 6.2.

4.3 Comparison with the Standards of Flight Safety

It was determined by way of introduction that the accident rate of today of accidents involving death per flight hour, and thus also the accident probability per hour, amounts to $3 \cdot 10^{-6}$ and that accident probability is identical with the malfunction probability of the technical apparatus in the case of an automation of the flight control processes. The malfunction probabilities of the historical as well as of the autopilots available today and a few proposals are noted in Table 46. Historical autopilots (first and second generations) show, compared with the third generation presently in use, somewhat smaller malfunction probabilities, which can be traced back to the slighter number of control functions as well as the comparatively simple structure. The third generation, operational in aeronautics at this time, shows a malfunction probability of $4 \cdot 10^{-3}$. Only the fourth generation shows malfunction probabilities through the use of redundancy, which lie only one order above the present accident probability.

The reliability of human piloting is thus at this time better by at least one order of magnitude of the accident probability (even by redundancy with two pilots).

If more authority is to be assigned to automatic flight piloting, resp. if man is to be completely removed from the control circles

of piloting in order merely to exercise a supervisory function, the malfunction probabilities of the automatic flight piloting systems, whose essential component must, of course, be a flight control system, would have to be lowered by two orders.

TABLE 46. MALFUNCTION PROBABILITIES OF AUTOPILOTS AND SYSTEMS PROPOSALS /130

	Year	Type	Manufacturer	Malfunction Probability within an hour Q·10⁶
Second Generation First	1932	A-2	Sperry	2,500+
	1938	K4U K 12	Siemens	1,100+
	1939-43	Lstz 14	Askania	2,000+
	1947-51	A-12	Sperry	6,000 - 2,000++
	1947-51	PB-10	Bendix	6,000 - 2,000++
	1960	PB-10A	Bendix	2,990++
Third Generation	1961	SEP-4	Smiths	1,740++
	1965	SP-30	Sperry	3,500++
	1964	PB-20D	Bendix	4,500++
	1965	L-102	Lear	4,400++
	1965	SP-50	Sperry	4,060++
Fourth Generation	1966	AFCS-VC-10	Elliot	12++
	1963	MH-123	Honeywell	1,900+
	1966	SEP-5 Duplex	Smiths	6,000+
		SEP-5 Triplex	Smiths	13+
Further Proposals		Duplex	-	6,000+
		Triplex	-	13+
		Triplex-Assemblies	-	12+
		Quadruplex	-	18+

+) Values based on a reliability analysis with malfunction probabilities of the assembly.

++) Values from data actually obtained in flight operations.

5. OPTIMIZATION OF SYSTEMS RELIABILITY

5.1 General Information

If the system consists of several components whose reliabilities p_i resp. malfunction probabilities q_i are known or can be calculated on the basis of their malfunction rates, /131

$$R = R(p_i, a_i) \qquad \begin{matrix} i = 1, 2, 3 \ldots n \\ a_i = 1, 2, 3 \ldots m_i \end{matrix} \qquad (21)$$

Two malfunction probabilities q_0 and Q_s must be assigned to the system resp. the components in a precise consideration, since each component in each system has two types of malfunction which have opposite effects on the systems reliability with alteration of the systems configuration. The types of malfunction are signal interruptions (zero signal-open circuit) and short circuit. The malfunction probability of a group formed from the components can not always be reduced by a parallel setup of components [122].

However, one type of malfunction will generally predominate, /132 i.e. one probability will be lodged with respect to the other, so that it is justified in first approximation to draw into the considerations only one malfunction probability.

This is especially the case if one considers the malfunction probabilities of autopilot-assemblies. These are, in general, designed in such a way that the type of malfunction is predominantly signalled interruption.

As is known, a reduction of the malfunction probability of the total system can be obtained by a parallel arrangement of systems or components.

This can be seen immediately. If, for example, the systems reliability

$$R = R(p, m)$$

is given to a redundant arrangement of equal components through

$$R = 1 - (1 - p)^m$$

whereby, p = survival probability of a systems component, of not malfunctioning through interruption,
m = degree of redundancy = number of components arranged in parallel fashion,

then for

$$\lim m \to \infty \;,\; R \to 1 \quad (p < 1)$$

resp. the malfunction probability

$$Q \to 0$$

The function R (p(t);m) is reconstructed in Figure 39.

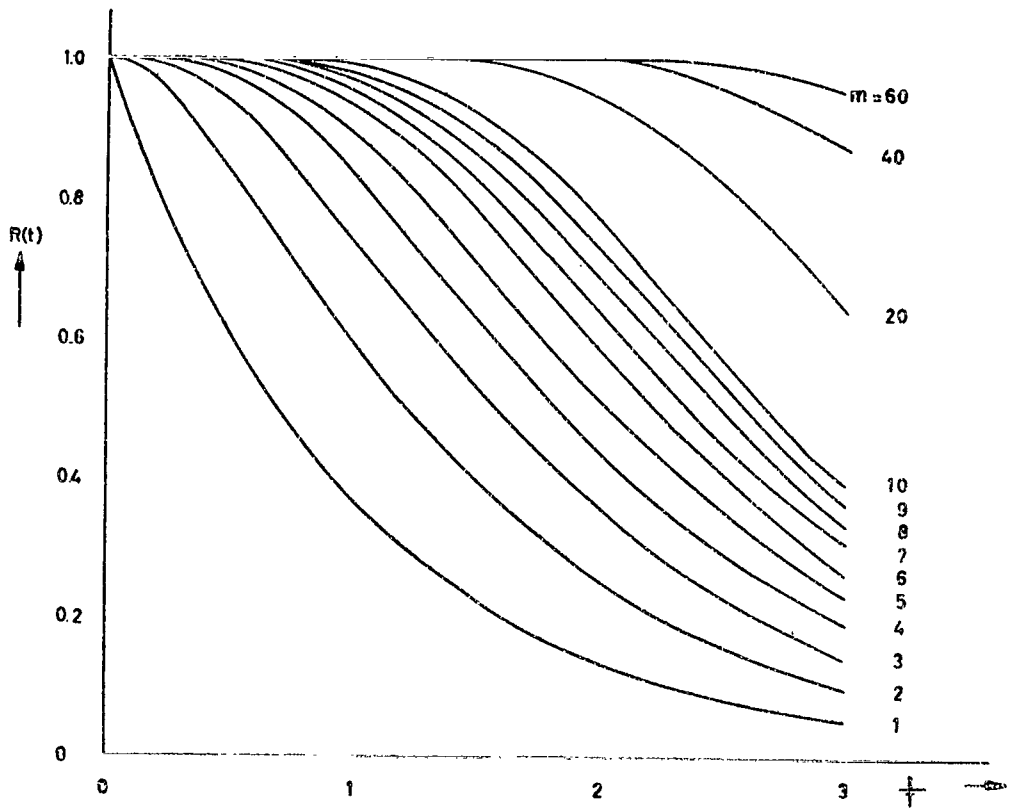

Fig. 39. Reliability of a Group of m Equal, Parallel Components (Type of Malfunction: Interruption). /133

5.2 Comparison of the Possible Systems Configurations /134

In order to carry out a systems optimization, it is purposeful to distinguish two cases:

1. The system is regarded as consisting of sub-systems (components, assemblies). The components have differing malfunction probabilities and, in a given case, malfunction types. The number of various assemblies necessary for systems operation is given.

The systems configuration can then be represented in the following way and is designated as a series system:

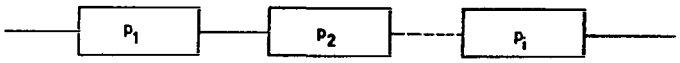

Fig. 40. Series System

The systems equation[11] of such a series system for the type of malfunction, interruption, is the known product formula

$$R = \Pi p_i \qquad i = 1, 2, 3 \ldots n \tag{22}$$

Malfunction Probability Q of the System is the sum of the individual malfunction probabilities /13

$$Q = \Sigma q_i \tag{23}$$

A variation of the series system is represented by the configuration reconstructed in Figure 41:

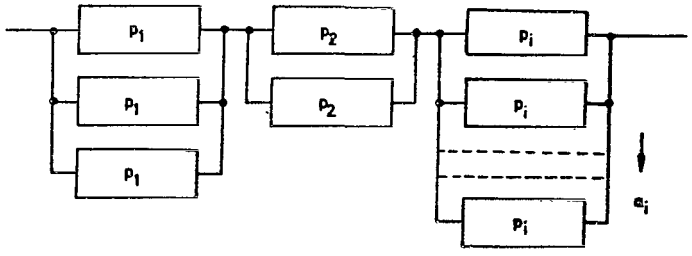

Fig. 41. Parallel-Series-System.

The individual components of the series system are replaced by parallel groups. However, a series-series-configuration is also possible, which contains increased reliability for the type of malfunction, short circuit.

The systems equation of the parallel-series-system reads for

---

[11] The probability from many events is calculated from the laws of the theory of probability, especially

1. The law of the complete additivity of probabilities (addition theorem).
2. The law of the multiplication of probabilities (Multiplication theorem).

Compare for that purpose [74-82].

the malfunction type, interruption:

$$R_{PS} = \prod [1 - (1-p_i)^{a_i}] \qquad i = 1, 2, 3 \ldots n \qquad (24)$$

2. The system is regarded as a unit; in a given case, a superordinate system is formed whose components consist of the originally present system.

Malfunction probability and malfunction type of the components of the newly formed system can be regarded as equal.

The number of components is freely selectable and can be one, if it corresponds to the demands of reliability. /136

The same manner of consideration can hold true for assemblies resp. other subsystems.

The systems configurations can then be represented as in Figure 42 and is designated as series-parallel-system.

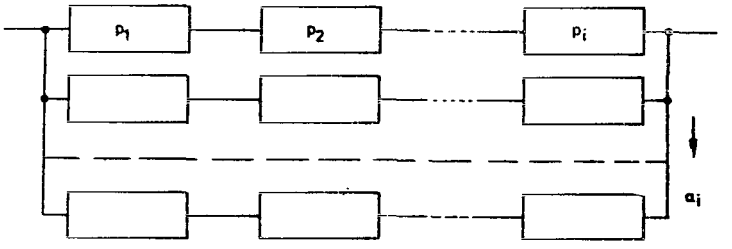

Fig. 42. Series-Parallel-System

If the primary system malfunctions predominantly through short circuit, a series-series-configuration can also offer advantages here.

The equation of the series-parallel-system reads:

$$R_{sp} = 1 - [1 - \prod p_i]^{a_i} \qquad (25)$$

Systems Properties

Both a series-parallel-system and a parallel-series-system have, with equal reliability of components, greater reliability than a series system. Moreover, it can be shown that a parallel-series-system always has for the malfunction type interruption a greater reliability with the same type and number of components than a series-parallel-system, if one forms difference function $R_D = R_{ps} - R_{sp}$. This always becomes larger than zero in the open

interval $0 < p < 1$.

This can be seen in a comparison of Figures 41 and 42, since with a parallel-series-configuration more operational paths are available, i.e. more partial malfunctions are permissible than in the case of a series-parallel-configuration.

However, a series-parallel-configuration is easier to realize from the point of view of construction, since the number of points of connection is slighter than in the case of parallel-series-redundancy. Series-parallel-system in the area of autopilots are frequently designated as multiplex-systems (eg SEP-5 of the Smiths).

5.3 Behavior of Systems Reliability with Alteration of Reliability of Components

It was determined in the preceding section that a parallel-series-system, i.e. redundancy of assemblies, should be chosen in the case of equal number and malfunction probability of the components if redundancy must be provided.

The question now arises, which assemblies should be made redundant.

A genuine optimization, i.e. a relative, maximal value of the systems reliability $R = R(p_i, a_i)$ in the open interval $0 < R < 1$, does not exist. The function $\underline{R}$ is monotonically gradient in the case of growing $\underline{p}$ and $\underline{a}$ (in the case of only one malfunction type of the component) in order to reach the absolute maximum $R = 1.00$ either for $p = 1$ or for $a \to \infty$ $(p < 1)$.

A criterion of optimization can, however, be formulated in the following way:

Sought after is the greatest alteration of systems reliability R with alteration of the reliability of its components $\underline{p}$ with given systems configuration.

Since these systems equations $R = R(p_i)$ are known, this problem can be solved with the help of the gradient method.

For the strongest alteration of the function $\underline{R}$ along one path s:

$$\frac{dR}{ds} = \pm\sqrt{\sum \left(\frac{\partial R}{\partial p_i}\right)^2} \qquad (26)$$

Series System

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The systems equation $R = p_i$ holds true.

Consequently, for the alteration of $\underline{R}$ with alteration of any p_i (p_j = const. for j + i)

$$\frac{dR}{dp_i} = \frac{R}{p_i}$$

$$\frac{d(\ln R)}{dp_i} = \frac{1}{p_i} \qquad (27)$$

The greatest alteration of InR and, because of the monotonicity of the logarithm, of $\underline{R}$ as well is thus inversely proportional to the absolute value p_i of any one assembly. One attains the greatest increment of systems reliability by improvement of the most unreliable component.

This result corresponds to the common ideas, according to which the weakest member of a chain breaks first.

Parallel-Series-System

If one now considers the case of the parallel-series-system whose equation reads

$$R_{ps} = \pi[1 - (1-p)^{\alpha}i]$$

then this can be transformed by the following substitutions

$$1 - p_i = q_i$$
$$q_i^{\alpha} = Q_i$$
$$1 - Q_i = P_i$$

into the form /139

$$R = \pi P_i$$

where p_i represents the reliability of the redundant assembly. The same considerations hold true for this equation as for the simple series system, i.e. one obtains the greatest increment of systems reliability $\underline{R}$ with use resp. further increase of the redundancy of the most unreliable assembly.

5.4 Procedures for the Design of a Highly Reliable System with given Reliability of its Components

If a standard of reliability is given for the system, which cannot be obtained by means of a simple series system as a result

of the insufficient reliability of its components, the standard of systems reliability can be met through a simple progressive method, in that the systems components are designed redundantly.

Methods (after Webster [123])

One orders the components in accordance with the magnitude of their malfunction probabilities. Then, one increases the degree of redundancy of the most unreliable systems component resp. redundant group by one, corresponding to that described above. After reordering of the component resp. redundant groups corresponding to the malfunction probabilities, one repeats the procedure. One calculates after each step the systems reliability. One repeats the procedure until the demanded reliability is attained.

5.5 Redundancy Types[12] /140

5.5.1 ACTIVE, FUNCTIONAL REDUNDANCIES

The possibility will be characterized as active, functional redundancy to realize a redundant arrangement of assemblies, constructional components, components without additional monitoring and switching (or switching redundancy, or selective switchings) (majority redundancy). That is, however, only possible in the case of a few components (eg. relays, switches, diodes, resistances, mechanical structures). The malfunction probability of a system of small and equal components of malfunction probability q is

$$Q = q^n$$

5.5.2 SEQUENCE OR SWITCHING REDUNDANCY

The possibility will be designated as a sequence redundancy (stand-by, sequence, sensing and switching) of switching by means of a monitor and switching unit from, to begin with, one component carrying out the function to the next operable component upon its malfunction.

At least two equivalent components are necessary for monitoring of defects, so that redundancy is only possible in the case of three components. However, for the most part pairs, i.e. at least four components, will find application for reasons of symmetry.

Assemblies for the purpose of defect monitoring and switching are described under 6 and 7.

---

[12] There is to date no agreement on the German language designations. Work is being done on a unified terminology in various working circles (NTG, VDI).

For the malfunction probability Q under neglect of the malfunction probability of defect monitoring and switching for one group of, in each case, two equal component pairs:

$$Q = (2q)^2 = 4q^2$$

For a system of three pairs of, in each case, two components: /141

$$Q = (2q)^3 = 8q^3$$

In general, for n components

$$Q = (2q)^{\overline{n}}$$

One advantage, as opposed to the majority redundancy described further below, is offered by sequence redundancy, if the assembly emits a continuous signal on its operability through internal monitoring arrangements, which can serve for the activation of a witching. This presence of such a signal can be set as a precondition for so called monitored assemblies in developments such s computers, amplifiers, uhf-vhf radio receivers. Then, the ecessity of the comparison of, in each case, two apparatuses no onger exists, and a sequence redundancy can be carried out with, n each case, one component.

Then, as in the case of active redundancy with neglect of witching:

$$Q = q^n$$

5.5.3 MAJORITY REDUNDANCY

The realization of redundancy can also be made possible by an arrangement ("Voter") which makes a selection from among the output signals of three or more redundant components arranged in parallel fashion (compare 6.2). The logic of a triplex electrohydraulic servo motor (compare 6.1) also follows the laws of a majority selection.

The majority principal does, however, cause deviating equations for systems reliability R and malfunction probability Q, as opposed to active functional redundancy, in the case of given reliability p and malfunction probability q of its components, which will be briefly considered in the following sections.

In Figure 43, the principal of the logic circuit for majority /142 redundancy with signals from the three components A, B, C is

presented. The equation of the logic read:

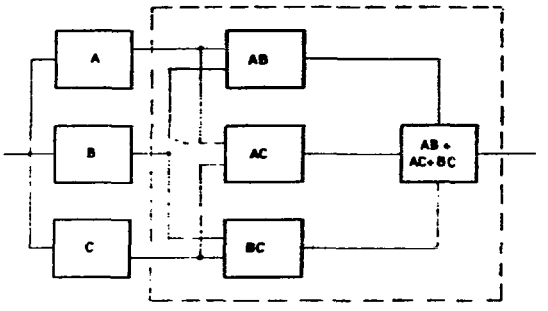

Fig. 43. Principal Circuit Diagram of a Logic Circuit for Majority Redundancy with Three Components.

$$L = AB + AC + BC$$

Under the assumption that $q_A = q_B = q_C = q$, a probability results that no output signal is present (malfunction probability)

$$Q_s = 3q^2 \qquad (28)$$

One can also obtain an expression for the reliability of such an arrangement of three equal components - to begin with, under neglect of the malfunction probability Q_V of the voter - through the expansion of the binomial expression

$$(p+q)^3 = 1 = p^3 + 3p^2q + 3pq^2 + q^2 \qquad (29)$$

in which the firm term p^3 indicates the probability that all three components will survive, the second that a defect will appear, the third that two defects will appear and the fourth that all three components will now function within the temporal interval under consideration. At least two components must survive in the case of a majority redundancy in order for the system to remain operable.

$$R = 1 - Q = p^3 + 3p^2 \cdot q; \quad q = 1-p$$
$$R(p(t)) = 3p^2 - 2p^3 \qquad (30)$$

The course of this function R(t) is presented in Figure 45.

The malfunction probability Q results here at

$$Q = 3q^2 - 2q^3$$
$$Q \approx 3q^2 \qquad q^3 \ll q^2$$

If one considers the voter reliability R_V, then

$$R = (3p^2 - 2p^3) R_V \qquad (31)$$

If the reduction of the systems malfunction probability attainable by means of the logic known to date for a majority redundancy of three components does not suffice, a logic circuit could be used for five components. It should be possible with such a logic to survive two malfunctions (the principal could be designated as "three of five".

The principal circuit diagram of such a logic is presented in Figure 44.

The logic consists of 10 AND-Gates with, in each case, three inputs of, in each case, three of the five redundant components A, B, C, D, E (the number of the possible permutation is $\binom{5}{3} = 10$). The output signal of the AND-Gate are lead to an OR-Gate whose output signal is present until more than two of the five components have malfunctioned.

The equation of the logic reads:

$$L = ABC + ABD + ACD + ACE + ADE + BCD + BCE + BDE + CDE$$

There results for the malfunction probability of the entire system under the precondition $q_A = q_B = \ldots q$: /144

$$Q = 10\,q^3 \qquad (32)$$

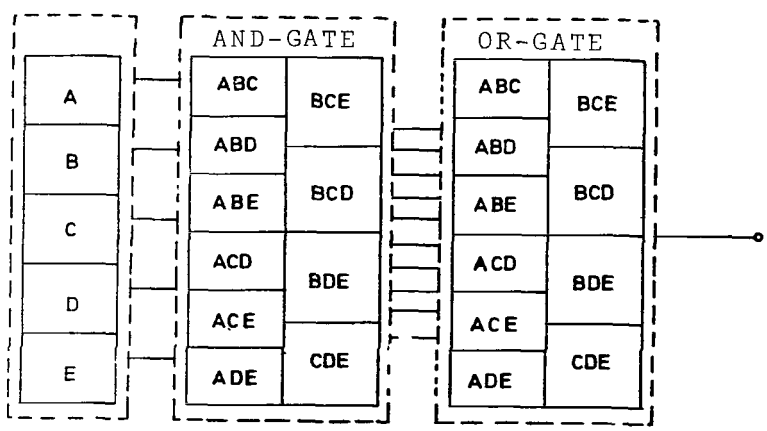

Fig. 44. Principal Circuit Diagram of a Logic Circuit for a Majority Redundancy with Five Components.

One can obtain here an expression for the systems reliability from the binomial development for five components.

$$(p+q)^5 = 1$$

The results

$$R = p^3[6p^2 - 15p + 10] \tag{33}$$

likewise

$$Q = q^3[6q^2 - 15q + 10]$$
$$= 10q^3 - 15q^4 + 6q^5$$
$$Q \approx 10q^3$$

under neglect of the members of higher order than q^3, since $q^4 \gg q^5$, $Q < 10q^3$ also follows.

Such logic represents a considerable output of switching, especially if the logic itself must be designed redundantly for reasons of reliability.

Mass and volume can, however, be held small enough with the help of integrated circuits, in order to guarantee a practical applicability.

The function R (p(t)) for five components is presented in Figure 45.

In general, the following binomial distribution holds true for n equivalent components:

$$(p+q)^n = 1 = p^n + n \cdot p^{n-1} \cdot q + \frac{n(n-1)\,p^{n-2}\,q^2}{2!}$$
$$+ \frac{n(n-1)(n-2)\,p^{n-3}\,q^3}{3!} + \ldots + q^n = \sum_{r=0}^{n} \binom{n}{r} p^{n-r} \cdot q^r$$

If n of the n components function, the following holds true for the total reliability R without consideration R_V of the voter

$$R = \sum_{r=m}^{n} \binom{n}{r} p^r \cdot (1-p)^{n-r} \tag{34}$$

It can be seen from Figure 45 that both the function $R = 3p^2 - 2p^3$ (3 components) and the function $R = p^3[6p^2 - 15p + 10]$ /147

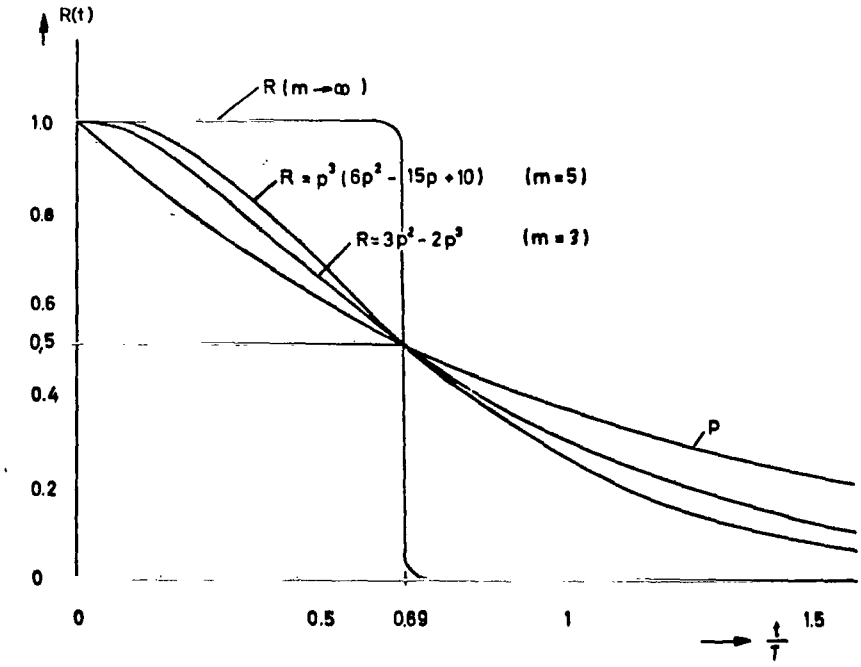

Fig. 45. Reliability in the Case of Majority Redundancy /146

(5 components) as well as any function R(p(t)0 in the case of majority redundancy intersect the course of reliability of the individual element $R = p = e^{-t}$. The point of intersection can be determined:

$$3p^2 - 2p^3 = p \Rightarrow p = 0{,}5$$

and also

$$p^3 [6p^2 - 15p + 10] = p \Rightarrow p = 0{,}5$$

The function $p = e^{-\frac{t}{T}}$ $(T = \frac{1}{\lambda})$ is intersected in each case in the point R = 0.5, i.e. a reliability increase is only present at times which are smaller than the time belonging to R = 0.5, $\frac{t}{T}$ = 0.69.

The possibilities described under 5.2 - 5.4 for the increase of systems reliability, which presupposes the systems equation for active systems redundancy, can be transcribed to majority redundancy without limitation.

Majority redundancy avoids the disadvantages of the redundancy with defect monitoring and switching which must function with conventional relays. "Voter" resp. semiconductor logic circuits can be made extremely reliable themselves (6.2), so that their mal-

function probability becomes negligibly small. An especial advantage is, moreover, a certain protection against short circuit malfunctions, i.e. input signals of extreme magnitude.

5.5.4 COMPARISON OF REDUNDANCY TYPES

The formulas of the malfunction probabilities Q are reconstructed in Table 47 for the various redundancy types and number of components of equal malfunction probability q under neglect of the malfunction probability of the components making possible the redundancy.

TABLE 47. RELATIONS BETWEEN SYSTEMS MALFUNCTION PROBABILITY Q AND MALFUNCTION PROBABILITY OF THE COMPONENT q IN THE CASE OF VARIOUS REDUNDANCY TYPES AND NUMBER OF COMPONENTS. /148

Redundancy Type	Number of Components with Malfunction Probability q				
Active Redundancy	q^2	q^3	q^4	q^5	q^6
Sequence Redundancy (Monitored Components)	q^2	q^3	q^4	q^5	q^6
Sequence Redundancy (Simple Components)	-	-	$4q^2$	-	$8q^3$
Majority Redundancy	-	$3q^2$	-	$10q^3$	-

It can be seen from Table 47 that the greatest reduction of the systems malfunction probability with the smallest number of necessary components is obtainable by means of active redundancy and sequence redundancy with "monitored components". These are, however, not always applicable. Majority redundancy offers advantages if only simple (not monitored) components are available for a sequence redundancy period.

6. SPECIAL ASSEMBLIES FOR THE CONSTRUCTIONAL REALIZATION OF REDUNDANCIES

6.1 Mechanical Assemblies

Mechanical assemblies find application especially in the control of the control surfaces. The best known possibility consists of realizing redundancy with the help of differential leverbars, as is schematically presented in Figure 46. Autopilot signals in manual control by the pilot operate in parallel fashion on the control by the pilot operate in parallel fashion on the control of the hydraulic rudder servo motor for the adjustment of the control surface, so that the manual control is conserved in case of malfunction of the autopilot and an overtravel of the autopilot is also possible. /149

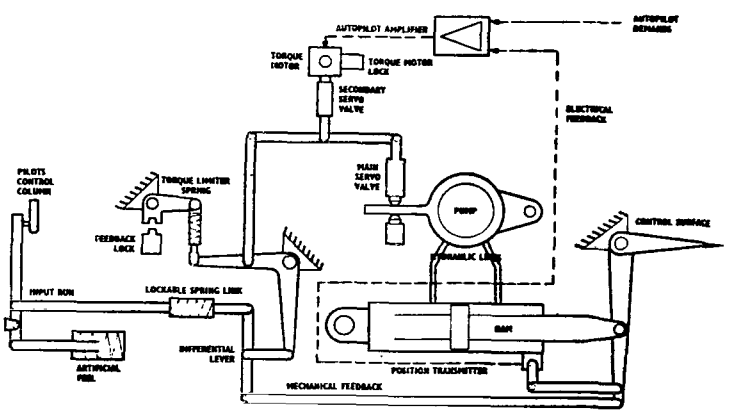

Fig. 46. Redundant Control by Pilot and Autopilot from [22].

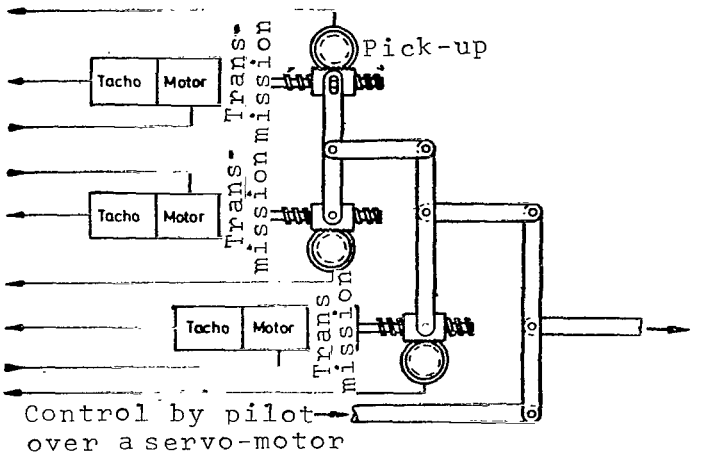

Fig. 47. Triplex Electromechanical Servo Motor [72] /150

The principal of a triplex electro-mechanical servo motor for control through three control chains and manual control by the pilot is presented in Figure 47 [72].

A further possibility for suviving a malfunction with three control signals can be established by a power coupling in electro-hydraulic servo motors. This possibility is provided, eg, by that of the firm Smith for the E + SEP-5 triplex system (Short-Belfast and H.S. Trident). The Fluggeratewerk Bodensee also uses the actuator of the firm Hobson presented in Figure 48 in the development of a triplex control [124, 125].

The control takes place through the three electro-hydraulic servo valves. The function is conserved if two valves obtain /151

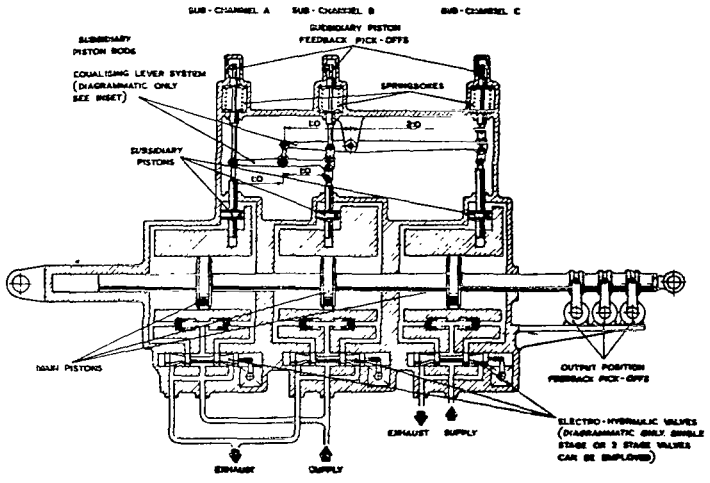

Fig. 48. Semischematic Presentation of the Triplex Servo Motor. [124, 125]

correct signals. This servo motor is further improvable by the planned feeding through three hydraulic energy sources independent of one another.

The indication of malfunction probabilities of the mechanical differential lever assemblies appears extraordinarily problematic. However, it might be negligibly small with painstaking dimensioning and choice of materials.

An estimation of the manufacture of the malfunction rate for the entire servo motor is available for the triplex electro-hydraulic servo motor of Hobson Ltd.:

$$\lambda = 100 \cdot 10^{-6}\ h^{-1}$$

A third of the above value results proportionately for one channel, thus

$$\lambda = 33 \cdot 10^{-6}$$

6.2 Electrical Assemblies /152

A mean value choice of the analogous control signals under consideration can be undertaken with the help of the analogously operating amplitude-selection-switching through so called voters. This principle was proposed for control purposes by Bendix [39, 40].

Such a voter consists of logic circuits, three "AND"-Gates and one "OR"-Gate, as presented in Figure 43.

Malfunction Probability of a Voter

The malfunction probability of a voter can be estimated on the basis of the malfunction rates of its constructional components (compare [40]) (9 diodes and 4 resistances), and it results in

$$q = 11 \cdot 10^{-6} \cdot t$$

Selection circuit from three voters.

An essential improvement of the malfunction probability can be attained if one constructs a selective circuit from three voters, as is demonstrated in Figure 49.

The malfunction probability then amounts to /153

$$Q = q^3 = 10^{-15} \cdot t^3$$

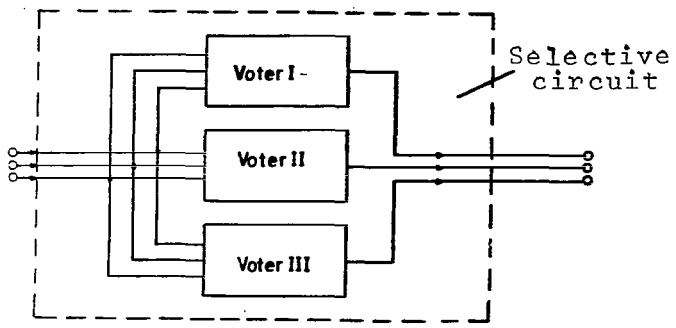

Fig. 49. Selective Circuit of Three Voters.

If the control takes place in impulse steady modulation procedure, the use of a similar circuit is possible. General Electric uses this principle (designated "Hydapt") in the autopilot system for the F-111 [36, 37]. The middle of three signals is likewise selected here for the purpose of control.

A constructively different principle, that of the sequence resp switching redundancies, for the switching off of a defective signal is shown by Figure 50. Two such monitors are provided in the piloting proposal of the Vereinigte Flugtechnische Werke [25, 26].

The entire monitoring and switching unit consists here of two identical assemblies M1 and M2. Each assembly can be split up into one part which lies in the signal flux, M_{11} resp. M_{21}, and one part which does not lie in the signal flux, M_{12} and M_{22}. /154

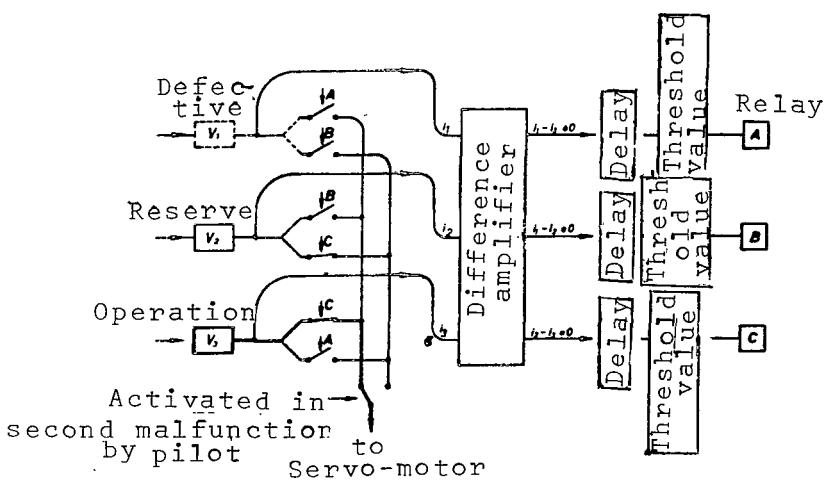

Fig. 50. Circuit for the Suppression of Defective Signal (Sequence resp. Switching Redundancy)

7. SETUPS FOR MONITORING

7.1 General Information

Redundancy only causes a smaller malfunction probability of the system if all redundant components are fully operable prior to beginning of operation, since, according to definition, the function of a redundant total system should also be conserved in the case of partial malfunctions, so that a monitoring is not possible through testing of the total function.

A self-test possibility of assemblies is also desirable in the case of malfunctions in simple systems, for the purpose of rapid localization of a defect.

Special setups for monitoring have been developed.

7.2 Gyros

A self-test device for miniature rate gyros [126] is presented in Figure 51.

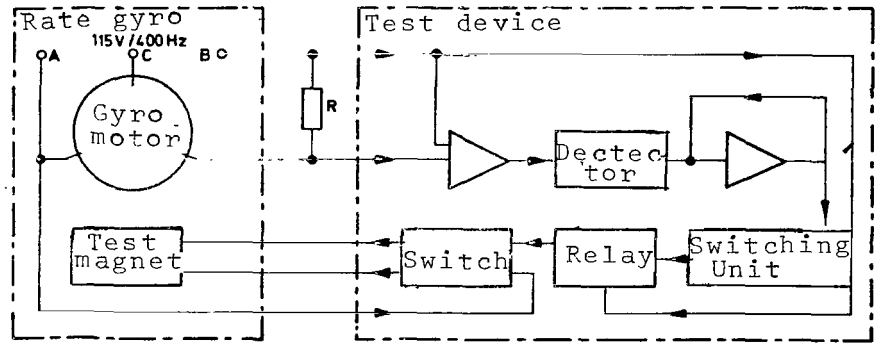

Fig. 51. Self-Test Apparatus for Miniature Rate Gyros. /155

The self-test apparatus consists of a test coil and a separate test amplifier. The test coil is shifted, outside of the gyro housing, over this. The gyro mechanism is not directly influenced by the test coil and a movement of the gyro is not necessary. The self-test apparatus allows one to recognize whether the gyro is running at the full rate of revolution and whether the frames are blocked.

Another principle for the checking of the functions of gyros is described in [127].

It can be recognized through turning of the gyros around the

test axis inclined to all three sensitive axes by 45° with a certain angular velocity, where all three gyros are emitting correct signals.

The firm Elliot also manufactures electrically caged control-rate gyros which are provided with an self-test apparatus.

7.3 Monitoring in the Case of Electric Signals and Assemblies /156

A monitoring in the case of several equivalent (redundant) electrical signals is possible with the help of difference amplifiers, each of which compares two of the signals and can control warning lights in the case of excess of a preselected difference. In order to be able to distinguish between a first defect and further defects, trigger circuits can be provided as defect stores. The principle of such a circuit is presented in Figure 52, which is provided as a monitor for a selective circuit with voters [29].

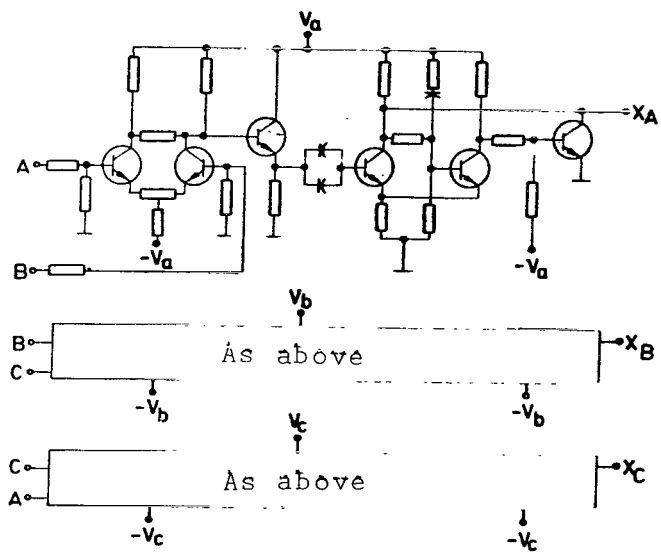

Fig. 52. Circuit Diagram of a Monitor with Difference Amplifier and Two Schmitt-Triggers

The warning lights have, in each case, two filaments which are switched by independent redundant circuits. This circuit is presented in Figure 53. /157

A circuit for monitoring with magnetic amplifiers of VFW is described [25, 26]; there, not only the malfunction is indicated by the monitor, rather also a switching from the malfunctioned to the redundant element. /158

The firm Elliot has developed a special form of indicator of

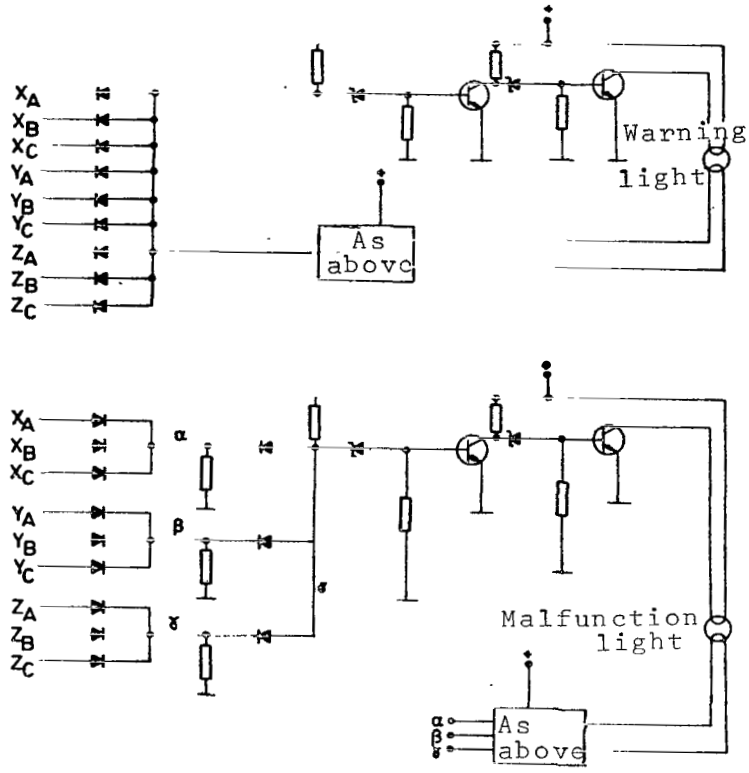

Fig. 53. Circuit for Warning Lamps (First and Second Malfunction) - after [39].

malfunctions in computers and amplifiers for autopilots and other practical purposes [21, 23]. Partial malfunction in redundant circuits in the computer are indicated on, in each case, one segment on an electro-luminescent light panel positioned at the front side of the apparatus; the panel is subdivided into many smaller segments. The number of malfunctioned circuits can be recognized by a glance at the lighting panel.

8. MODEL DESIGN OF HIGHLY RELIABLE FLIGHT CONTROL SYSTEMS

8.1 General Information

It was shown in 4.3 that the flight control systems available today are not sufficient to the point of view of safety to guarantee an automatic piloting without continuous supervision by the pilot and the thereby provided redundancy.

It will be shown subsequently that it would be possible with the findings of the preceeding section on the optimization of systems configurations and procedures of reliability increase to design highly reliable flight control systems corresponding to the standards of flight safety even with the relatively unreliable assemblies available today.

The solution of a similar problem was first demonstrated by Moore and Shannon [128] in the example of circuits of unreliable relays. Special systems properties result in the case of redundant systems, which have, to date, retarded the further application of the known connection between redundancy and reliability.

These are especially: /159

1. Increased mass, volume and costs in the initial creation and installation of redundant systems.

2. Poorer maintenance and more expensive upkeep of the redundant systems and the necessity of special testing arrangements.

If, however, the standards for higher systems reliability have precedence, then there exists only the possibility of redundancy if the reliability of the functional groups and assemblies does not suffice to give to a simple system the demanded reliability.

The malfunction probabilities of the assemblies are, corresponding to the state of technology, used as a basis in the case of the redundant autopilot models designed in the following sections in systems for the purpose of automatic piloting. These malfunction probabilities result from the (assumed as constant) malfunction rates of the assemblies noted in 2.3.1.5, which are reconstructed in summary in Table 43.

Systems should be regarded as models, which are not fitted to special aircraft types in control-technical respects and in which constructive points are not carried out in detail. They should document the performability and systems configurations of highly reliable control systems, which could serve the purpose of making feasable the complete automation of part of flight piloting,

not only from the functional side, rather also from the point of view of flight safety.

Use is made in the design of the various redundancy types as well as of the procedures and points of view described in the preceeding section. To a large extent, use is made of majority redundancy as a redundancy type, since "monitored" assemblies are not available at this time.

8.2 Model of a Stabilizing and Damping Gyro /160

The malfunction probabilities of the assemblies which are needed for a pure stabilizing and damping gyro for three axes are reconstructed in Figure 48 according to magnitude of their malfunction probability. The malfunction probabilities result, in accordance with the relation

$$q = 1 - e^{-\lambda t} \approx \lambda t$$

from the (assumed as constant) malfunction rates of the assemblies after Table 43. An exception was made in the case of the control unit, for which $100 \cdot 10^{-6}$ was set in use, since the value cited in Table 43 of $350 \cdot 10^{-6}$ rests on the entire control device (flight controller and mode selector). The mode selector, however, belongs to the steering control circuits.

TABLE 48. FOR CALCULATION OF THE MALFUNCTION PROBABILITY OF A NON-REDUNDANT STABILIZING AND DAMPING GYRO

Assembly	Malfunction Probability $q \cdot 10^6 \cdot t$	Number of Necessary Assemblies N	Malfunction Probability $N \cdot q \cdot 10^6 \cdot t$
Position Gyro	500	1	500
Computer-Amplifier (Roll)	500	1	500
Computer-Amplifier (Pitch)	500	1	500
Computer-Amplifier (Yaw)	125	1	125
Flight Controller	100	1	100
Rate Gyro	70	3	210
Servo Motor	65	5	315
			2350

The results for a simple system /161

$$Q = 2350 \cdot 10^{-6} \cdot t \ .$$

Since each individual assembly has a malfunction probability which is already larger than the standard with respect to systems malfunction probability ($Q \leqq 10^{-6}$ t), as a first step all assemblies can be triplex-redundantly designed (majority redundancy). For that purpose, the voters described in 6.2 and under 5.5.3 are necessary (aside from in the case of the use of the triplex hydraulic servo motor), whose malfunction probability amounts to $q_V = 10^{-15}$ t^2 and is thus negligibly small, which should also be presupposed for the "3 of 5 logic". Duplex active redundancy (m = 2) is provided for the control unit.

TABLE 49. CALCULATION OF REDUNDANCY OF A STABILIZING AND DAMPING GYRO.

No. of necessary assemblies N	Assembly	Malfunction Probabilities q [10^{-6} t]	q^2 [10^{-9} t^2]	$3q^2$ [10^{-9} t^2]	$10q^3$ [10^{-9} t^3]
++)		(m=1)	(m=2)	(m=3)	(m=4)
1	Position Gyro	500	-	750	1.25
1	Computer-Amplifier (Roll)	500	-	750	1.25
1	Computer-Amplifier (Pitch)	500	-	750	1.25
1	Computer-Amplifier (Yaw)	125	-	48	0.02
1	Control Unit	100	10	-	-
3	Rate Gyro	70	-	15(45)+	0.003 (0.01)
4	Servo Motor	65	-	13(52)+	-

+) Numbers in parentheses indicate the total malfunction probability N ($3q^2$ resp. N) (10q) in the case of needed assemblies

++) M = Number of parallel redundant assemblies.

The malfunction probability of the stabilizing and damping gyro, which would function with triplex majority redundancy up to the duplex active redundant control unit, amounts to, as can be calculated from Table 49, /162

$$Q = 2{,}4 \cdot 10^{-6} \cdot t^2$$

This malfunction probability is already smaller by 10^{-3} (for t = 1) than that of the simple control after Table 48. However, it does not yet correspond to the standards. These are only fulfilled by a system in which the position gyro as well as the computer-amplifiers and rate gyros would be used, in each case, five-fold. The malfunction probability Q becomes

$$Q = 62 \cdot 10^{-9} \cdot t^2 + 3{,}78 \cdot 10^{-9} \cdot t^3$$

It then would result for one hour (t = 1) a malfunction probability of

$$Q = 65{,}78 \cdot 10^{-9}$$

8.3 Model of a Steering and Stabilizing Flight Control System

If a stabilizing gyro is to carry out the function of steering, then piloting magnitudes from corresponding location sensors are necessary. The choice, which piloting magnitude from the available location sensors is to be modulated, is made by the pilot, in each case, according to flight phase, over the mode selector by means of activation of appropriate switches. The choice of azimuthal and vertical piloting magnitudes is possible independent of one another. The contribution of the location sensor to the total malfunction probability must remain so small for the reliability of such a conventional steering and stabilizing gyro that, also, the standard of malfunction probability is not exceeded.

The location sensors usual at this time as well as their malfunction probabilities are noted in Table 50. The malfunction probabilities of the corresponding switches in the control unit are to be contained in these values.

It can be seen that triplex majority redundancy would not suffice to hold small enough the malfunction probability, rather that five components would be necessary. /163

TABLE 50. CALCULATION OF THE REDUNDANCY OF LOCATION SENSORS

Assembly	Malfunction Probabilities q $[10^{-6} \cdot t]$ (m=1)	$3q^2$ $[10^{-9} \cdot t^2]$ (m=3)	$10q^3$ $[10^{-9} \cdot t^3]$ (m=5)
1 VOR/LOC-Receiver	1,000	3,000	10
1 Compass Course Gyro System†	800	1,920	5
1 Air Data Sensor and Computer	500	750	1.25
1 Glide Path (ILS) Receiver	500	750	1.25

† Estimated malfunction rate

The contribution of the location sensors, which are operated in majority redundancy, to the systems malfunction probability would then amount to

$$Q = 17{,}50 \cdot 10^{-9} \cdot t^3$$

If these location sensors were not used redundantly, the contribution to the malfunction probability would be

$$Q = 2{,}800 \cdot 10^{-6} \cdot t$$

With use, of in each case, three components in majority redundancy

$$Q = 6{,}42 \cdot 10^{-6} \cdot t^2$$

8.4 Model of an Expanded Steering and Stabilizing Control System /164

Such a system should contain further functions as opposed to the steering and stabilizing controls considered previously:

1. Automatic landing.

2. Automatic takeoff (overshoot go-around)

For that purpose, the following assemblies would be necessary in addition:

1. A radio altimeter as well as a computer-assembly ("Flare Computer") are necessary for automatic landing as sensors for the pitch position piloting. Aside from that, an automatic auto throttle is necessary whose input signals could derive from the air data transmitter.

2. A further computer-assembly ("Take-off and Overshoot", "Take-off Computer") as well as additional sensors, flap position indicators, accelerometers, and incidence angle indicators is necessary for the automatic take off system. Aside from that, signals of the position gyro and air data indicator (static and Pitot) already belonging to the system serve as input variables.

The contribution of the additionally necessary assemblies /165 to the systems malfunction probability would amount to with five fold installation of the computers and the radio altimeter

$$Q = 24{,}6 \cdot 10^{-9} \cdot t^2 + 2{,}06 \cdot 10^{-9} \cdot t^3$$

that would be for t = 1

TABLE 51. CALCULATION OF THE REDUNDANCY OF ADDITIONALLY NECESSARY ASSEMBLIES OF AN EXPANDED STEERING AND STABILIZING CONTROL SYSTEM.

Assembly	Malfunction Probability q $[10^{-6}/t]$	q^2 $[10^{-9}/t^2]$	$3q^2$ $[10^{-9}/t^2]$	$10q^3$ $[10^{-9}/t^3]$
	(m=1)	(m=2)	(m=3)	(m=5)
1 Radio Altimeter	500	-	750	1.25
1 Computer (Flare-Computer)	300	-	270	0.27
1 Computer (Autothrottle)	300	-	270	0.27
1 Computer (Take-off and Overshoot	300	-	270	0.27
4 Flap Position Indicators	40	1.6(6.4)	-	-
2 Accelerometers	50	-	7.5(15)	-
2 Incidence Angle Indicators	40	1.6(3.2)	-	-

$$Q = 26{,}66 \cdot 10^{-9}$$

If only triplex majority redundancy were to find application,

$$Q = 1{,}58 \cdot 10^{-6} \cdot t^2$$

Without redundancy

$$Q = 1{,}740 \cdot 10^{-6} \cdot t$$

8.5 Model of a Fully Automatic Flight Piloting System

A fully automatic flight piloting system should, aside from the manually selectable functions such as automatic landing and automatic take-off and flight, contain the programmed automatic course of all flight phases (take-off, long distance flight with several sections, landing). In addition to the assemblies of the systems considered to this point, a central navigation computer, eg, an inertial location system would be necessary as a location sensor.

It can be seen from Table 52 that these assemblies would also /166 have to be used fivefoldly in order to hold small enough the contribution of

$$Q = 44{,}07 \cdot 10^{-9} \cdot t^3$$

In the case of only triplex majority redundancy:

TABLE 52. CALCULATION OF THE REDUNDANCY OF THE NECESSARY ADDITIONAL ASSEMBLIES FOR A FULLY AUTOMATIC FLIGHT PILOTING SYSTEM

/166

Assembly	Malfunction Probabilities q $[10^{-6} \cdot t]$ (m = 1)	$3q^2$ $[10^{-9} \cdot t^2]$ (m = 3)	$10q^3$ $[10^{-9} \cdot t^3]$ (m = 5)
1 Inertial Navigational System	1,500	6,750	33,80
Computer	300	270	0,27
1 Navigation Computer	1,000	3,000	10,00

$$Q' = 10 \cdot 10^{-6} \cdot t^2$$

Without redundancy

$$Q = 2{,}800 \cdot 10^{-6} \cdot t$$

8.6 Summary

The calculated malfunction probabilities are compiled in Table 53. It can also be seen here that a majority redundancy with three components would not suffice to fulfill the demand for a malfunction probability $Q < 10^{-6}$ per hour. This could only be fulfilled in the case of use of majority redundancy with expensive application, of, in each case, five components.

However, this means a very high expenditure in terms of costs, /167 mass and volume of the system.

TABLE 53. SUMMARY OF MALFUNCTION PROBABILITIES

Systems	Malfunction Probabilities Simple System $[10^{-6}]$	Majority-Redundancy (Triplex) $[10^{-6}]$	Majority Redundancy (Fivefold & Triplex) $[10^{-9}]$
Stabilizing and Damping Gyro	$2{,}350 \cdot t$	$2.4 \cdot t^2$	$62 \cdot t^2 + 3.78 \cdot t^3$
Steering Control Circuit (Location Indicator)	$2{,}800 \cdot t$	$6.42 \cdot t^2$	$17.50 \cdot t^3$
Expanded Steering Control Circuit (Additional Assembly)	$1{,}740 \cdot t$	$1.58 \cdot t^2$	$24.6 \cdot t^2 + 2.06 \cdot t^3$
Fully Automatic Flight Piloting System (Additional Assemblies)	$2{,}800 \cdot t$	$10.0 \cdot t^2$	$44.07 \cdot t^3$

If assemblies were availabe which would make possible the application of sequence resp. switching redundancy, malfunction probability smaller by the factor of 10 could be obtained with application of, in each case, three assemblies.

The following malfunction probabilities result after Table 53:

1. For a flight control system of conventional type, but with, in each case, five resp. three components. These are listed

For one hour (t = 1)	$Q = 83.28 \cdot 10^{-9}$
For ten hours (t = 10)	$Q = 27.48 \cdot 10^{-6}$

2. For a flight control system with automatic take-off and automatic landing. /168

For one hour (t = 1)	$Q = 109.94 \cdot 10^{-9}$
For ten hours (t = 10)	$Q = 32 \cdot 10^{-6}$

3. For a fully automatic flight control system

For one hour (t = 1)	$Q = 154 \cdot 10^{-9}$
For ten hours (t = 10)	$Q = 76 \cdot 10^{-6}$

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